

# Advanced Gas Turbine

# ACT

## Technology Project

DOE/NASA/0168-6

NASA CR-168325

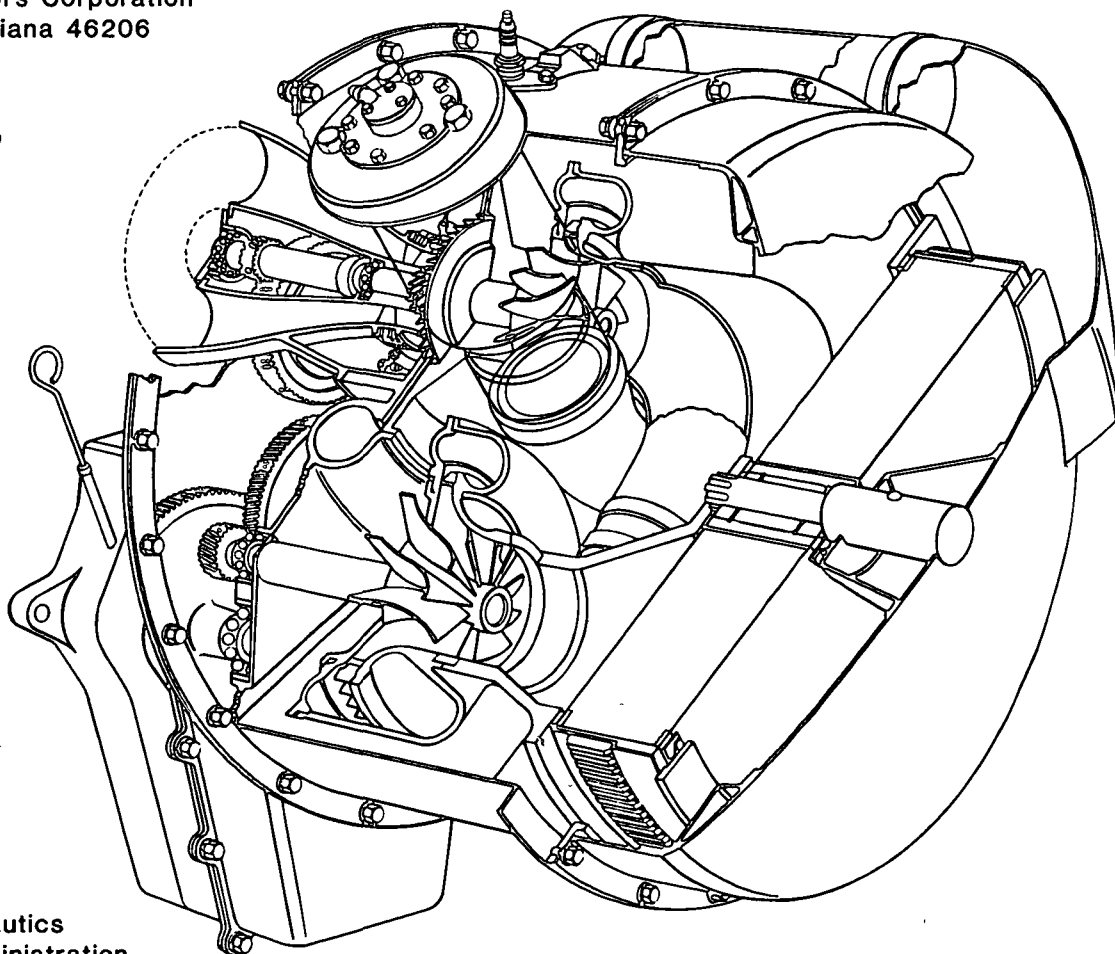
DDA EDR 11443

### Sixth Semiannual Report

For work performed from 1 July 1982 - 31 December 1982

Allison Gas Turbine Operations  
of General Motors Corporation  
Indianapolis, Indiana 46206

May 1983



Prepared for  
National Aeronautics  
and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135  
Contract DEN 3-168

For U. S. Department of Energy  
Conservation and Renewable Energy  
Office of Vehicle and Engine Research and Development

# **Advanced Gas Turbine AGT Technology Project**

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The basic objective of this project is to develop and demonstrate, by May 1985, an advanced automotive gas turbine that will, when installed in a 1985 Pontiac Phoenix vehicle of 1360 kg (3000 lbm) inertia weight, achieve a fuel economy of 18 km/L (42.5 mpg), will meet or exceed the 1985 emission requirements, and will have alternate fuel capability.

Several General Motors Divisions and other companies are major contributors to this effort. They are as follows: Pontiac Motor Division—vehicle and cost studies, Delco Remy Division—starter/boost motor, Corning Glass Works—regenerator, The Carborundum Company and GTE—ceramics.

The Allison Program Manager for the AGT 100 is H. E. (Gene) Helms; design effort is directed by Leonard Lindgren; materials effort is directed by Dr. Peter Heitman; and project effort is directed by Richard Johnson and Samuel Thrasher. The Pontiac effort is headed by Leighton Smith. The NASA AGT 100 Project Manager is Paul T. Kerwin.

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# SUMMARY

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## ENGINE DEVELOPMENT

The goal of the first year of engine testing is to accomplish engine familiarization and shakedown of mechanical systems.

This reporting period began with the first build of the AGT 100 engine on 9 July 1982, and during the remainder of the calendar year, five builds had been evaluated. Each build successfully corrected the reason for terminating testing of the previous build; steady progress was recorded during the period. The engine structure, bearings, oil system, and electronic control have been successfully demonstrated, with no shaft dynamics or other vibration problems encountered. Areas identified during the most recent series of tests which require modification are scroll retention features, and transient thermal deflection of the gasifier and power turbine backplates. Engine and backplate modifications have been analyzed and designed and are in the fabrication process. Testing with these new turbine components will begin early in calendar year 1983.

## GASIFIER TURBINE DEVELOPMENT

Engine testing has revealed insufficient gasifier turbine rotor clearance on the scroll side and the backplate side of the rotor. These interferences originate from two different sources. The scroll-to-rotor rub is caused by inadequate scroll retention at higher gasifier speeds. The backplate rub is caused by the thermal deflection during transients, especially the start transient. Both of these situations have been analyzed and modifications have been defined. Scroll retention is being addressed by modifying the seal arrangement in front of the gasifier turbine assembly, which will increase the pressure load on the scroll in the forward direction and thereby increase the retention forces. The backplate thermal deflection is being addressed by geometric changes and thermal insulation to reduce heat input. Analytically, these changes have been demonstrated as good solutions and hardware is being fabricated for engine testing.

## POWER TURBINE DEVELOPMENT

The development activities identified for the gasifier turbine are similar for the power turbine because of the geometric similarity of design. Scroll retention and backplate thermal deflection have been analytically studied, modifications have been defined, and hardware fabrication has been started. Engine testing will occur simultaneously with the gasifier component evaluations.

## COMBUSTOR DEVELOPMENT

Combustor rig proof testing of two ceramic combustor assemblies has been completed. Except for the combustor domes, two sets of ceramic components (combustor body, pilot tube, and dilution bands) have been qualified for engine testing. One ceramic dome failed during the first assembly proof test. The second dome survived the test but cracked during a subsequent oxidation heat treatment. The combustor dome design has been modified to incorporate slots and reduce sharp edges, which should reduce thermal stresses. Additional ceramic combustor rig testing will be conducted as more ceramic parts become available. Proof testing of the modified dome will begin as parts arrive. A metal dome with similar geometric shape will be used for interim rig and engine test work.

## REGENERATOR DEVELOPMENT

The evaluation of regenerator system flow distribution revealed significant potential losses in regenerator effectiveness due to maldistribution of flow. Design modifications, which have regained almost all of the lost effectiveness with only a small increase in pressure drop, were incorporated into the regenerator cover. Both the regenerator system effectiveness and pressure drop are now within 0.5% of design goals, as demonstrated by hot rig testing. Regenerator drive system development has passed through the rig development test phase with acceptable results and is ready for incorporation into the engine.

## CONTROLS DEVELOPMENT

The initial electronic control system hardware has been bench tested, has interfaced successfully with test stand systems, and has been very instrumental in successfully controlling and protecting the engine during the engine testing to date. The control has demonstrated versatility and ease of modification (software) to comply with changing demands dictated by early engine development problems.

## MATERIALS DEVELOPMENT

Rotor attachment/thermal barrier work has progressed at Carborundum Company (CBO) using mullite and at Allison using zircon. The development work has focused on techniques to sinter these barrier materials onto the ceramic rotors with successes for both material systems.

# Advanced Gas Turbine

# AGT

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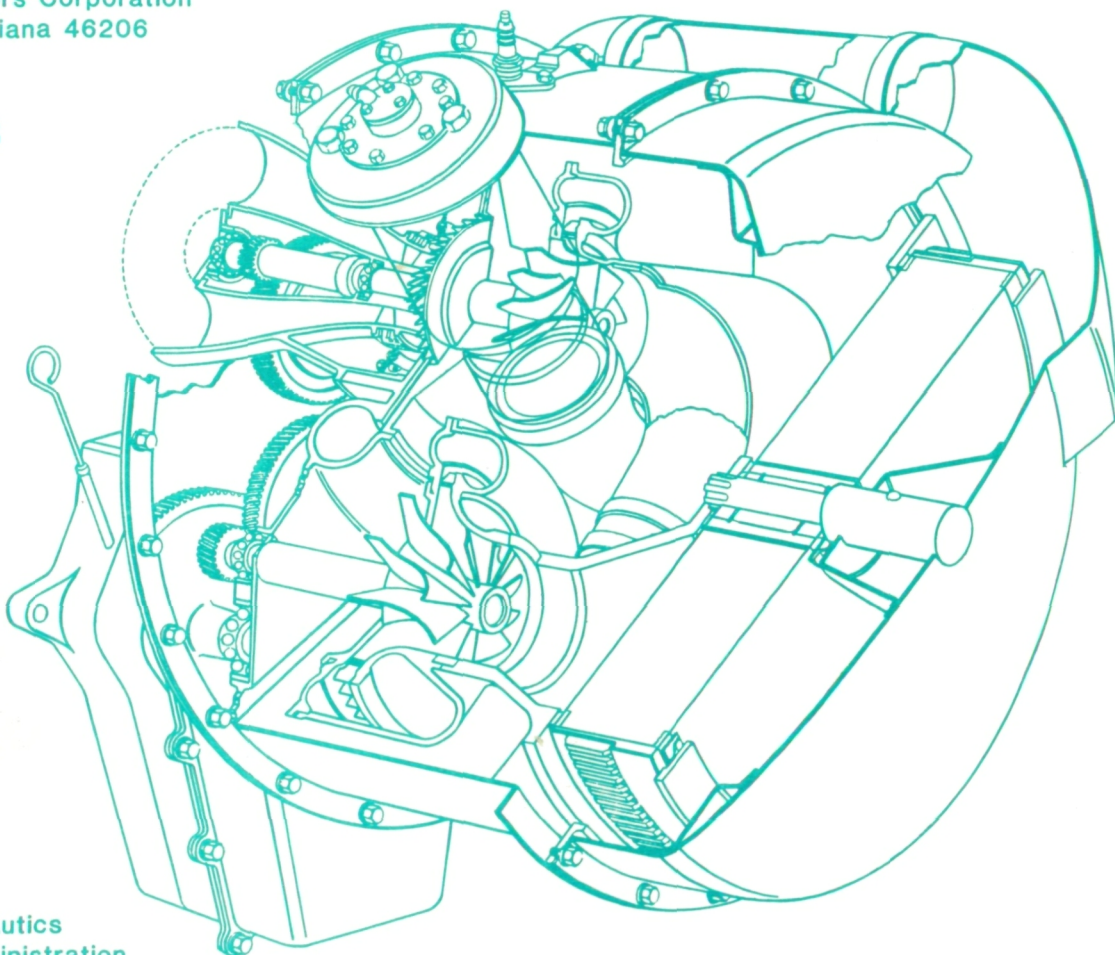
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### **NOTICE**

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Silicon carbide structural parts have been fabricated and tested. These include engine configuration gasifier rotors (ECRs), preliminary gasifier scroll parts, and gasifier

and power turbine vanes. Spin tests of initial ECR ceramic rotors and thermal shock rig tests of vanes have been conducted.

# INTRODUCTION

This is one of a series of semiannual reports documenting work performed on an Advanced Gas Turbine (AGT) power-train system development project for automotive applications. The work is being conducted by Allison Gas Turbine Operations of General Motors Corporation under NASA/DOE contract DEN-168.

The objectives of the project, as highlighted in Table I, are to develop an experimental power-train system that demonstrates the following: (1) the potential of a combined cycle fuel economy of 17.9 km/L (42.5 mpg) using diesel fuel No. 2 in a 1985 Pontiac Phoenix of 1364 kg (3000 lbm) weight on a 15°C (59°F) day; (2) emission levels less than Federal standards; and (3) the ability to use a variety of fuels. It is intended that the technology demonstrated through this project would assist the automotive industry in making a go/no-go decision regarding the production engineering development of gas turbine power trains.

In meeting the project objectives, the engine will be designed to accomplish the following, also outlined in Table I: (1) achieve reliability and life comparable to conventional 1985 vehicles; (2) achieve initial and life-cycle power-train costs competitive with 1985 power trains; (3) demonstrate vehicle acceleration suitable for safety and maneuverability; and (4) meet 1985 Federal vehicle noise and safety standards.

Initially, the project scope included the fabrication and chassis dynamometer testing of the engine, transmission, and electronic control system installed in a 1985 Pontiac Phoenix passenger car. However, Government funding constraints after the first year made it necessary to reduce the program scope.

Activities eliminated included fabrication and testing of the transmission and vehicle. The electronic control scope was narrowed from that of controlling the engine, transmission, and vehicle to controlling an engine on a dynamometer. Figure 1 depicts the activity areas and schedule for the revised project.

The AGT 100 design has been matched to the Pontiac Phoenix X-body car, shown in Figure 2. A front-wheel drive car, the Phoenix represents the current generation of ad-

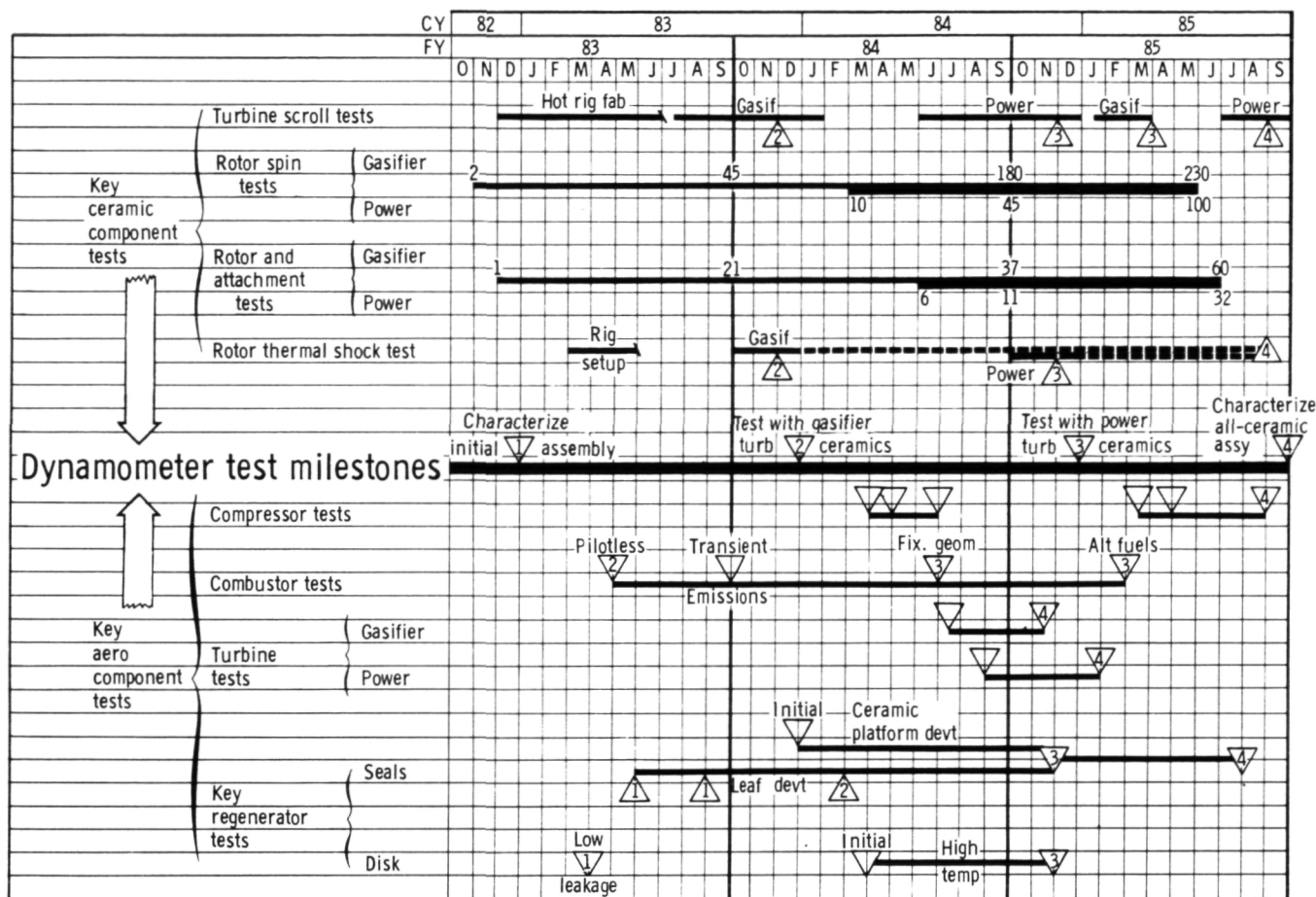
vanced passenger cars, emphasizing efficiency of space and weight to combine comfort and function with high fuel economy. The AGT 100 will also fit into the Pontiac A6000, an A-body car that is slightly larger and is the latest GM front-wheel design with potential to replace the X-body car in the Pontiac future marketing of cars.

The AGT 100, shown in Figures 3 and 4, is a two-shaft, regenerative gas turbine engine. In all respects, this engine design is tailored for high-volume application to fuel-efficient passenger cars. Its two-shaft configuration allows (1) the use of conventional transmissions, manual or automatic, and (2) turbine tip speeds (approximately 503 m/s [1650 ft/sec]) commensurate with available ceramic material properties (strength and variability). Single-shaft configurations were rejected by Allison because of the corresponding requirement for a continuously variable transmission and for approximately 40% higher turbine rotor ceramic material strength (for equal reliability). Careful attention was given to component arrangement for both vehicle installation and management of potentially high heat losses. All hot-section components are grouped together, bounded on one end by the regenerator, on the other end by the gearbox, and enclosed by a well-insulated cylindrical case. High-cycle temperature is possible through the use of ceramic hot-section parts. This, coupled with high aerodynamic component efficiencies, produces low fuel consumption and a 50% improvement in composite miles per gallon (30% energy efficiency improvement) in a Pontiac Phoenix. Most importantly, the AGT 100 uses existing technologies for shafts, bearings, cases, control system, accessories, etc., and thereby provides a reliable test device for evaluating ceramic and aerodynamic components.

The main development challenges in the program are in building small, high-performance gas turbine components and developing ceramic components for the required high engine cycle temperatures that are price competitive and can be produced in an automotive production environment. The AGT 100 ceramic components are shown in Figure 5.

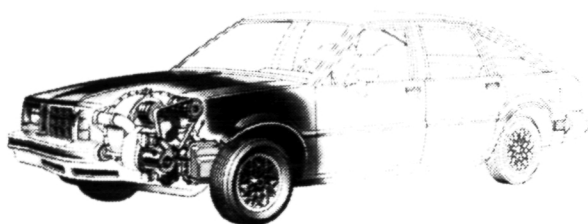
Table I.  
AGT 100 project and design objectives.

Project objectives	System design objectives
<ul style="list-style-type: none"><li>• 17.9 km/L (42.5 mpg) in 1985 Pontiac Phoenix</li><li>• alternate fuels capability</li><li>• meet 1985 emission standards</li></ul>	<ul style="list-style-type: none"><li>• comparable reliability and life</li><li>• competitive initial and life-cycle costs</li><li>• competitive accelerations</li><li>• meet noise/safety standards</li></ul>



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Figure 1. AGT 100 project plan.

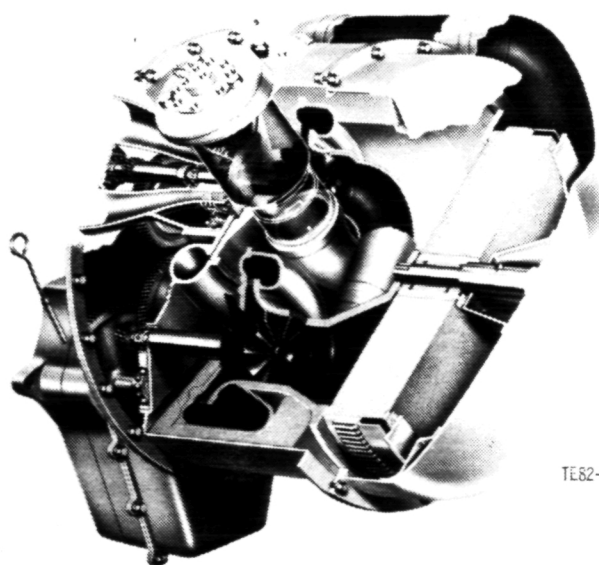


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Figure 2. AGT 100 engine in Pontiac Phoenix X-body car.

Because of the small-size engine (0.35 kg/s [0.76 lbm/sec] airflow), extensive rig testing, outlined in Table II, is being performed in component development. A major ceramic component development program is being pursued, and the ultimate success of the engine depends on the success of this activity.

Mechanical development of the engine is being conducted in two essential phases. The first incorporates early available ceramic components with metal substi-



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Figure 3. AGT 100 advanced gas turbine engine.

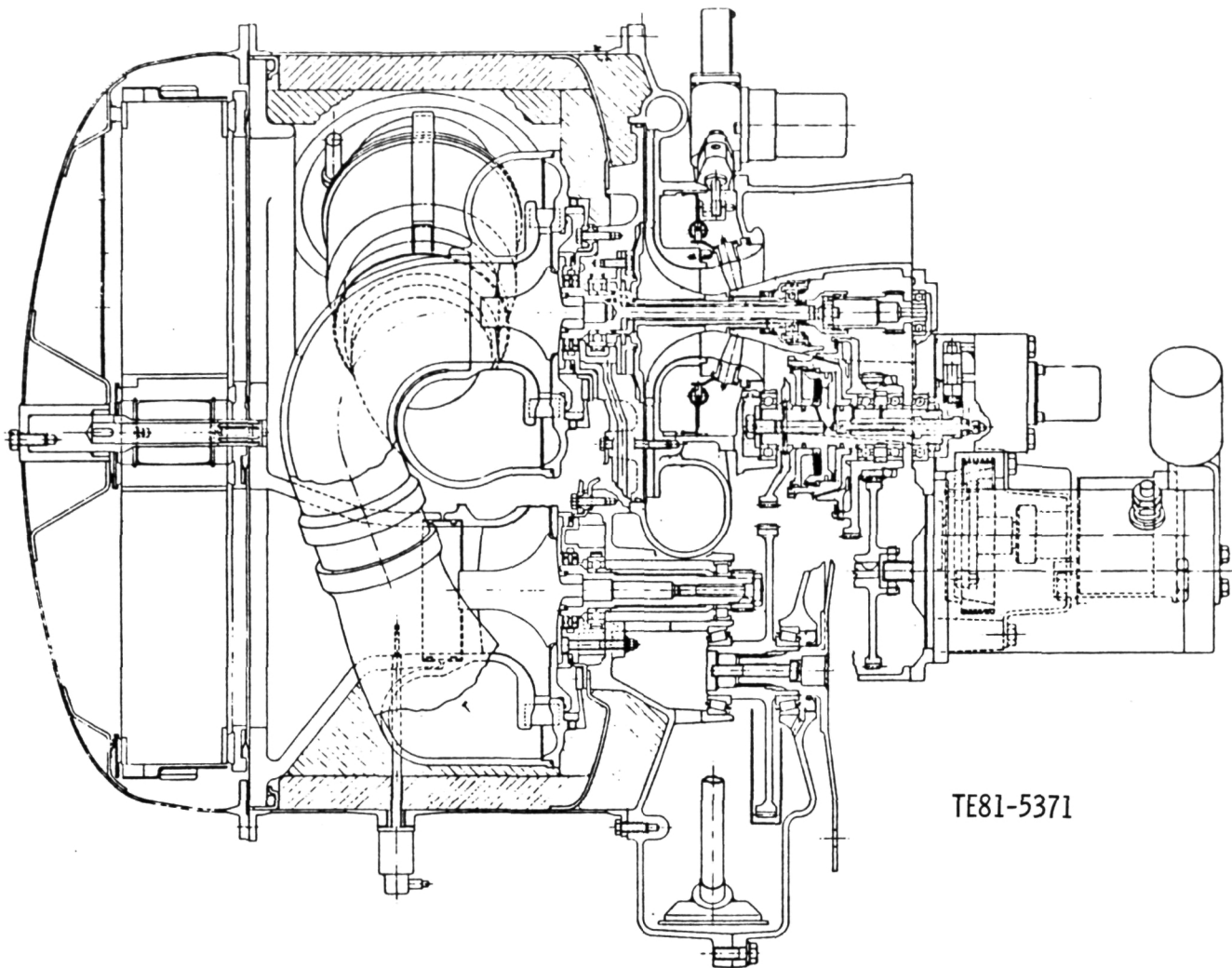


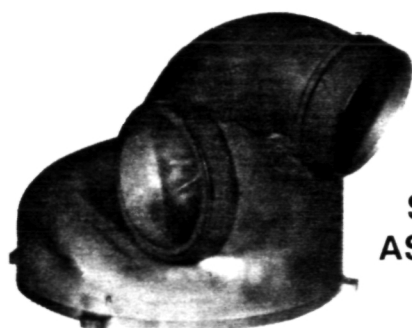
Figure 4. AGT 100 gas turbine engine general arrangement.

Table II.  
Aerodynamic component rigs.

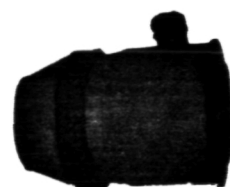
Component	Buils	Hours
Compressor	5	286
Combustor	7	132
Turbines		
Gasifier	2	204
Power	1	26
Interturbine duct	3	239
Regenerator		
Cold side flow distribution	8	110
Hot side flow distribution	1	72
Seal leaf leakage	4	35
Hot simulator rig	2	220
Ceramic seal platform	Two units	20
		1344

tutes for those components requiring further ceramics development. This phase includes metal turbine rotors and engine operation at 1079°C (1975°F) turbine inlet temperature. The second phase includes engine demonstration of all ceramic component types of 1288°C (2350°F) turbine inlet temperature. The transition from the first to second phase will occur in steps as each new ceramic component becomes available.

A team concept is used in this project, with many of the team members being General Motors Divisions. Allison is the prime contractor and team leader with responsibility for the overall power train and controls. Pontiac Motor Division (PMD) has vehicle design and cost analysis responsibility, and Delco Remy will develop the starter/boost system for the engine. The primary non-GM groups on the team are Carborundum Co. (CBO), Corning Glass Works (CGW), and GTE Laboratories, Inc., who are involved in the ceramic effort.



**SCROLL  
ASSEMBLY**



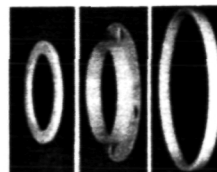
**COMBUSTOR**



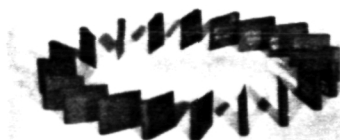
**TURBINE ROTOR**



**SEAL**



**THERMAL BARRIERS**



**TURBINE  
VANES**



**SCROLL  
BACKPLATES**



**REGENERATOR SEAL  
PLATFORM AND DUCT**



**REGENERATOR**

TE82-5884

Figure 5. AGT 100 ceramic components.

## II. ENGINE DEVELOPMENT

The goal of Mod I engine testing in the first year is engine familiarization and shakedown of mechanical systems. It is desired to establish the AGT 100 engine as a credible machine for evaluation of ceramic components and to identify engine interaction of components. This process will yield early identification of engine-related mechanical and aerodynamic problems, define component performance to compare with rig results, suggest development emphasis for future rig work, identify engine-related ceramic component problems or improvements required, and demonstrate control system and instrumentation adequacy.

One engine was initially obtained to accomplish normal shakedown activity, which kept parts rework to a minimum for subsequent engines and was compatible with project funding. Most of the parts for the second engine were obtained with the initial engine, but many parts were not finish machined until initial engine running revealed important clearances and adjustments to geometries, lubrication, and instrumentation systems, and until other normal engine shakedown development revealed adjustments. The goal of the Mod I engine testing is to achieve

100% speed and 1080°C (1976°F) operating temperature by the end of the first year of testing, while demonstrating the use of initial ceramic components.

### 2.2 MOD I (1080°C [1976°F TIT])

The first engine build and installation on the test stand was completed in July 1982. Photos showing the test stand installation are shown in Figure 6 and Figure 7.

This first engine build, designated Build 1 (BU1), contained several ceramic flow-path parts. These were as follows:

- ceramic combustor parts (body, pilot flame holder, dilution band)
- ceramic turbine vanes, both gasifier and power turbine
- ceramic regenerator seal platform
- ceramic regenerator disk

The engine fuel control used in early testing is semi-automatic. During an engine start, the sequencing of starter, fuel flow, and light-off functions is automatic. There is manual control of the start/main fuel nozzle se-

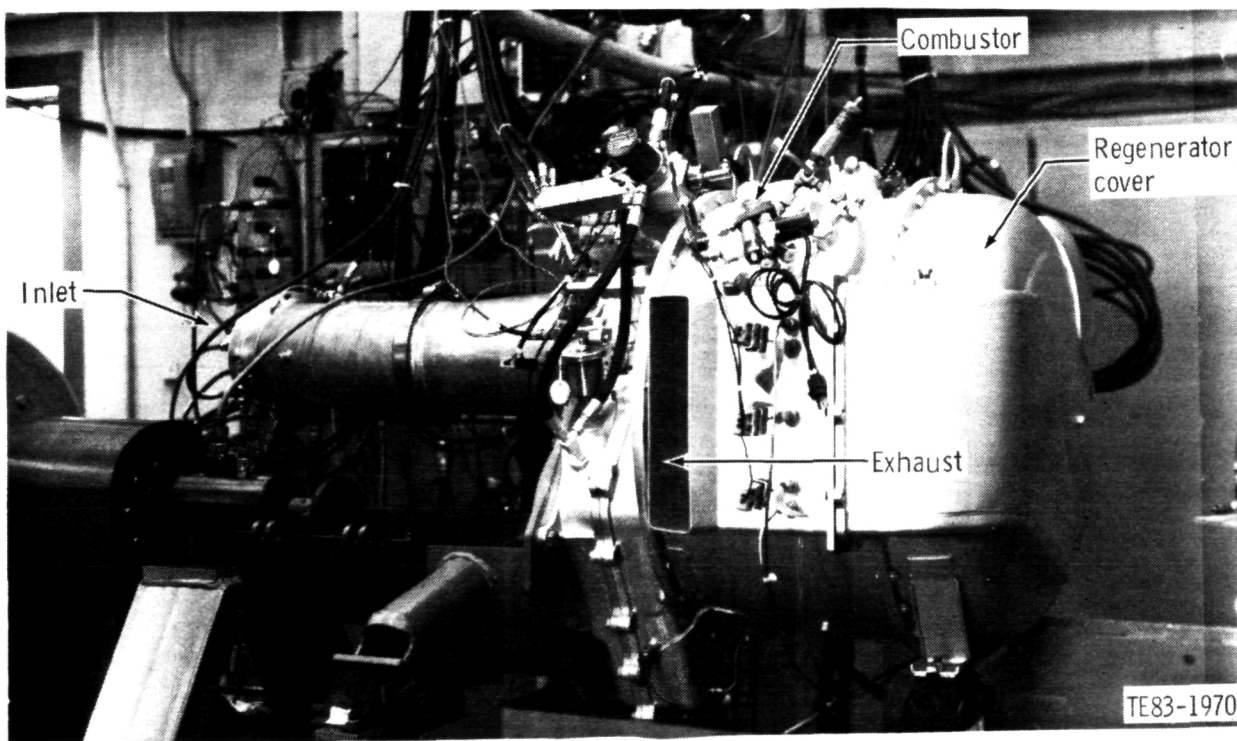


Figure 6. AGT 100, Mod I, rear view, being installed on test stand.

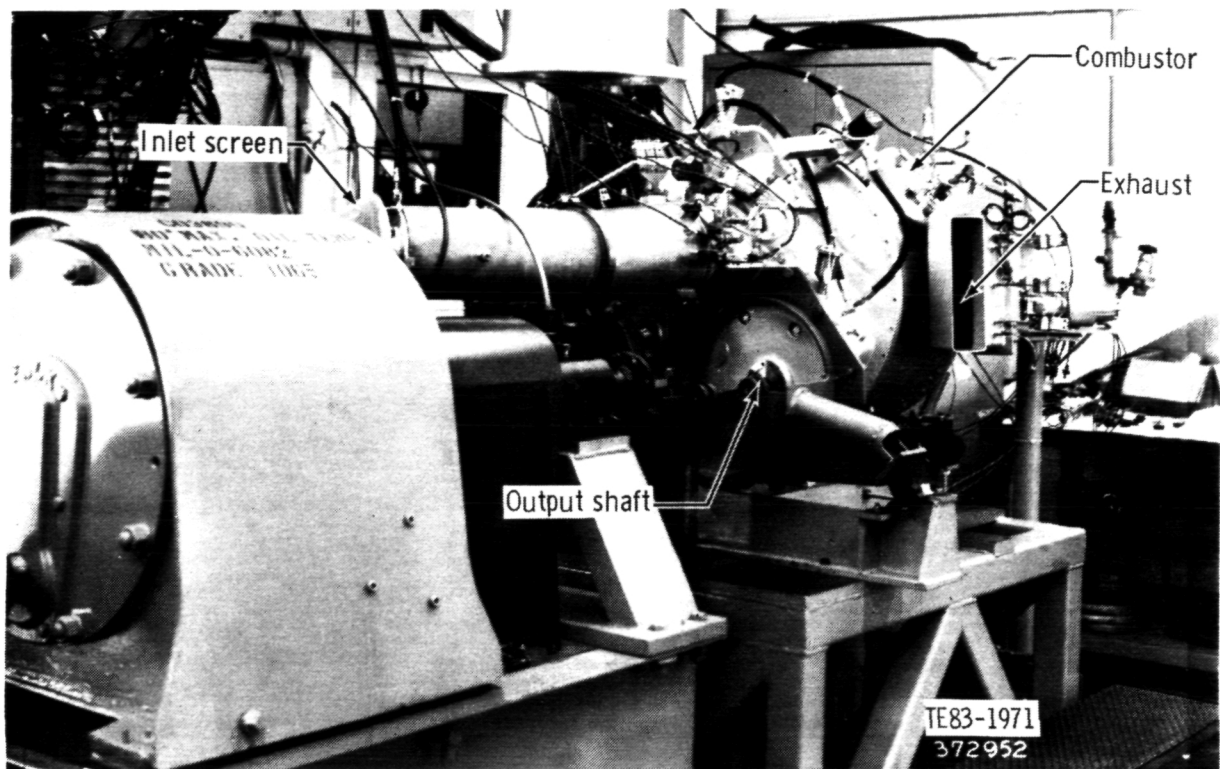


Figure 7. AGT 100, Mod I, being installed on test stand.

lection, the compressor inlet guide vane (IGV) angle, and the burner variable geometry position, as well as the governed speed.

The goal of early engine testing was to accomplish mechanical shakedown runs. Instrumentation was limited to that appropriate for hardware safety and test trouble shooting. Included in the engine build are proximity indicators, referred to as rub pins, to indicate actual minimum running clearance between the rotating wheels (compressor and turbine) and the stationary structure.

There were five engine builds and test programs during this reporting period. The first two involved several motoring tests and fuel control checkout tests. The following describes each build in detail. Also described are those tests that are significant with respect to performance or mechanical integrity.

### BU1 Test

The purpose of this initial test was to shake down the test stand and check out engine operation by means of motoring runs and a fire-up and stabilization at 60% gasifier section speed.

Testing was initiated with motoring of the two rotor systems. The Delco Remy starter was used to motor the gasifier rotor, and the test stand motoring dynamometer

was used to drive the power turbine. These early motoring tests resulted in the following:

- No abnormal noises were detected.
- Starter driven gasifier speeds of 30,000 rpm (35%) were obtained when voltages available to the starter were at automobile installation values.
- Oil pressure was developed as expected.
- Variable geometry actuation was as expected.
- Power turbine speeds to 20,000 rpm (30%) were run.
- No excessive vibration indication was observed.
- Test stand and instrumentation were checked.

The initial motoring tests revealed an inadvertent undersizing of starter internal wiring. Since correcting the starter wiring, operation of the starter has been satisfactory.

While correcting the starter wiring, operation was changed to locked power transfer clutch. An external test equipment oil pump was installed to provide oil pressure to the clutch at zero speed, since the engine oil pump is driven by the gasifier shaft. With this setup, the dynamometer was used to motor the engine with the gasifier and power turbine shafts locked in synchronization. These additional motoring tests were carried to 60% speed (51,800 N1, 40,900 N2). All mechanical parameters continued to be within limits.

Engine light-off tests were run with the clutch locked.

Pilot flame light-off was successful, but subsequent start nozzle light-off was not. An adjustment of light-off speed and of burner variable geometry position failed to allow a light-off. A review of the data available from engine running and component rig tests indicated that airflow to the combustor might be too low. Since the accuracy of airflow data at the low engine speeds encountered was questionable, further motoring was done with a smaller, more accurate airflow measuring orifice. The flow measurements obtained confirmed earlier data suggesting that operation during the light-off attempts was at the compressor surge limit. A further test was run with the combustor center-body assembly removed, which provided a large over-board bleed. These data showed a rematch of airflow and pressure ratio, which confirmed proper flow capability from the compressor.

The conclusion reached from the testing described was that when the start attempt was made with synchronous speeds, the relatively high speed of the power turbine resulted in a reduction in its flow capacity. This low power turbine flow capacity forced the compressor operating line into surge. The resulting flow pulsation prevented the start nozzle from lighting. The explanation for this sensitivity to turbine speed can be obtained from the rig measured flow map, shown in Figure 8. Radial inflow turbines have the characteristic of requiring a significant expansion ratio just to maintain a zero-flow condition, especially at higher corrected speeds. This expansion ratio is required to overcome the centrifugal force field of the rotor. The compressor pressure ratio must nominally equal the product of the two turbine expansion ratios. Slowing the power turbine down (by motoring only the gasifier) lowers the required compressor pressure ratio and this moves its operating point away from surge.

This is only a problem during starting when gas temperatures in the turbine section are essentially ambient. With the combustor operating, gas temperatures rise significantly and yield much lower turbine corrected speeds.

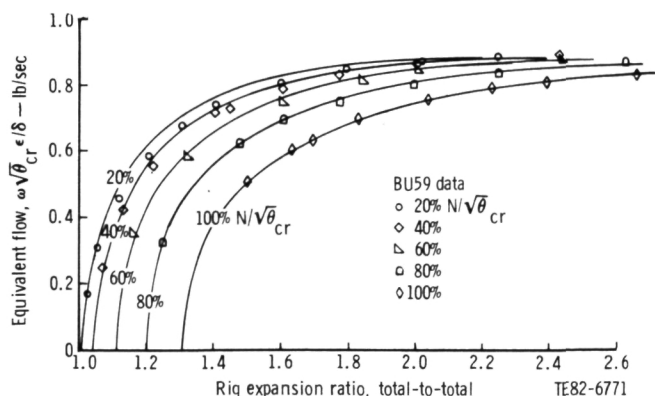


Figure 8. Power turbine experimental flow map.

During the test run with bleed, high deflection on the gasifier shaft was encountered. This deflection of the gasifier shaft was indicated by a proximity probe located at the compressor coupling region of the gasifier shafting system. Reseating of the coupling and adjustments to the front shaft bearing failed to eliminate the shaft deflection. The engine was then completely disassembled. Inspection showed that a self-centering iron ring seal between the compressor and turbine had rubbed the rotor shaft, generating excessive heat locally on the shaft assembly. A sleeve on the shaft at this position yielded. The resulting deformation allowed the rotor system to bend permanently, producing the observed proximity probe signal.

## BU2 Test

The engine was rebuilt with a carbon seal replacing the iron seal ring. Initial tests on this second build were motoring runs confirming that there was no shaft deflection. Testing then continued toward a light-off and a stabilized operation at 60% speed.

After the pilot flame was obtained, the start nozzle fuel ignited with no problem. Maximum temperature reached was low, 430°C (800°F), on the first start nozzle light-off. Several more starts were made with adjustments to the fuel schedule. Temperatures during start were eventually as high as 980°C (1800°F) at 68% speed, without self-sustained engine operation being achieved.

Typical engine transient response during these start attempts is shown in Figure 9. Temperatures and gasifier speed are shown versus elapsed time. The graph shows light-off peak temperature to be about 815°C (1500°F). The speed rose to about 68% and then decayed. For this run, the control governing speed was set to 70% speed. The turbine inlet temperature (TIT) had not risen above 815°C (1500°F) by the time peak speed was reached, but did rise to about 980°C (1800°F) when speed had decayed to about 52%. Starter shutoff occurred shortly thereafter. It was clear that speed decay occurred even though energy available (TIT) increased. Thus it was concluded that thermal effects and/or mechanical drag caused an increase in the required-to-run TIT beyond what was available. Additional starts were attempted with generally similar results obtained.

A routine borescope examination showed broken turbine vanes, and the engine was removed from the test stand. Disassembly of the engine showed the following:

- all gasifier turbine rotor inducer blade tips were uniformly broken approximately 9.5 mm (0.375 in.) from the outside diameter
- all ceramic vanes in the gasifier and power turbines were damaged
- rub on the rear of the gasifier turbine rotor and its associated backplate had occurred
- rub on the gasifier rotor exducer had occurred, and

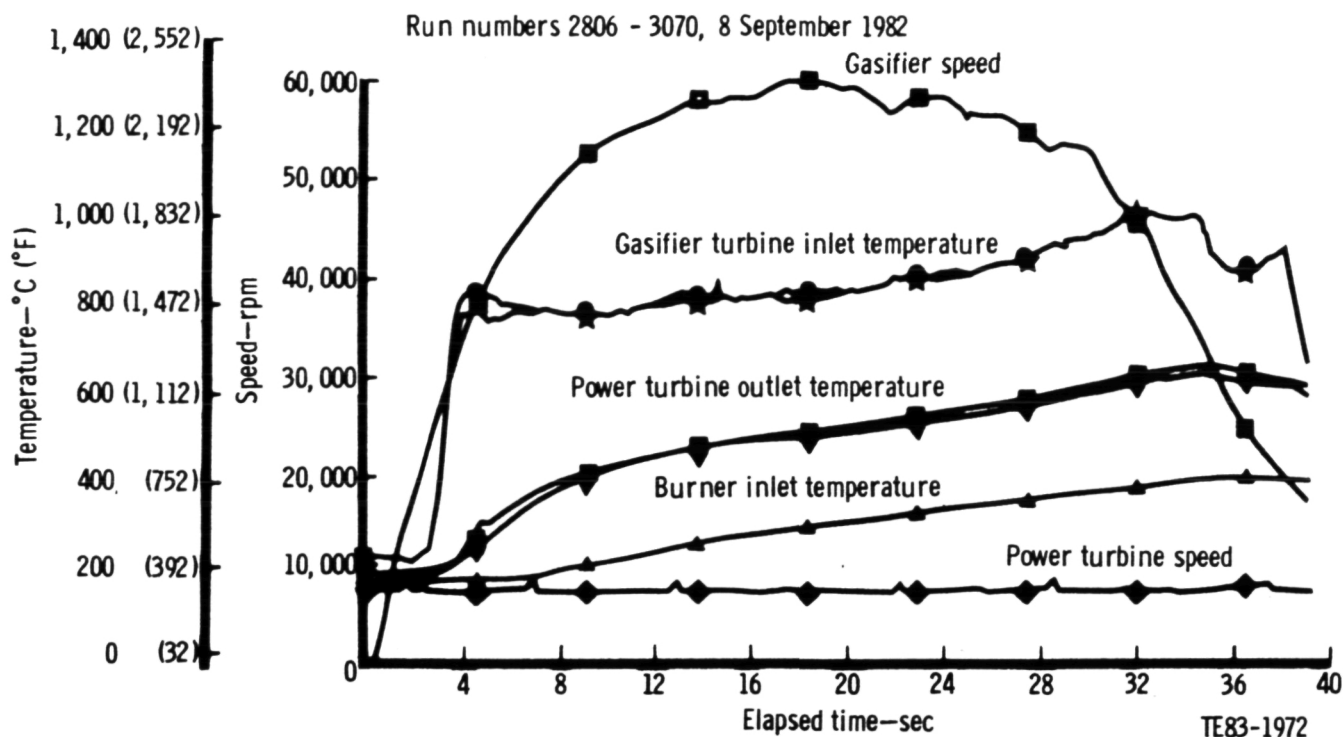


Figure 9. Start transient, BU2.

- rotor material had adhered to the shroud surface
- light power turbine rotor rub had occurred with very light debris damage to the rotor blades
- regenerator disk was slightly scored

A thorough failure analysis concluded that the most likely primary failure was the loss of the gasifier rotor inducer blade tips due to fatigue caused by heavy rub. A positive determination of fatigue was impossible because of impact damage on the blade tip fracture surfaces. The source of heavy rub was determined to be caused by an unseating and the resultant cocking of both scrolls due to air loads exceeding spring retention force. This determination was based on the rub patterns of the various parts, condition of the rub pins, and calculations of the net forces acting on the scrolls. The damage to the ceramic vanes, clearly secondary, was caused by rotor debris.

### BU3 Test

For the third build, configuration changes were made to correct the cause of BU2 failure. As a precautionary measure, all gas-path rub pins were removed. The turbine scroll retaining loads were increased by adding springs and by reducing a static load imposed by the combustor assembly. Metal vanes were used to expedite build, since a second proof-tested set of ceramic values was not available.

Clearances were improved on the gasifier turbine, and gas-path instrumentation was added between turbines. The power transfer clutch inner cone was omitted to preclude any inadvertent drag. The control was modified to permit additional maximum fuel flow.

Testing continued with a target of achieving stabilized operation at 60% speed. Two normal starts were made, the second of which reached governing speed and a brief period of self-sustained operation. However, shortly thereafter, speed decayed rapidly. Temperature recordings showed a rapid rise in temperature of the gasifier backplate, indicating a rub. The engine was removed from the test stand for disassembly and inspection.

A plot of engine speed and various temperatures versus time is shown in Figure 10. Starter drop occurred automatically at 53% speed, at about 7.5 sec elapsed time. Light-off TIT peaked at about 980°C (1800°F) and fell back to 870°C (1500°F) at starter drop. After the starter dropped, speed sagged. TIT then increased by automatic control action to achieve the preset governing speed of 60%. This speed was reached at about 22 sec, at which time the control appropriately cut back fuel to prevent overspeeding. Speed started to decay abruptly at about 26 sec. A curve showing the surface temperature of the gasifier turbine inner backplate is also shown in Figure 10. The abrupt increase in temperature at 27 sec indicated the oc-

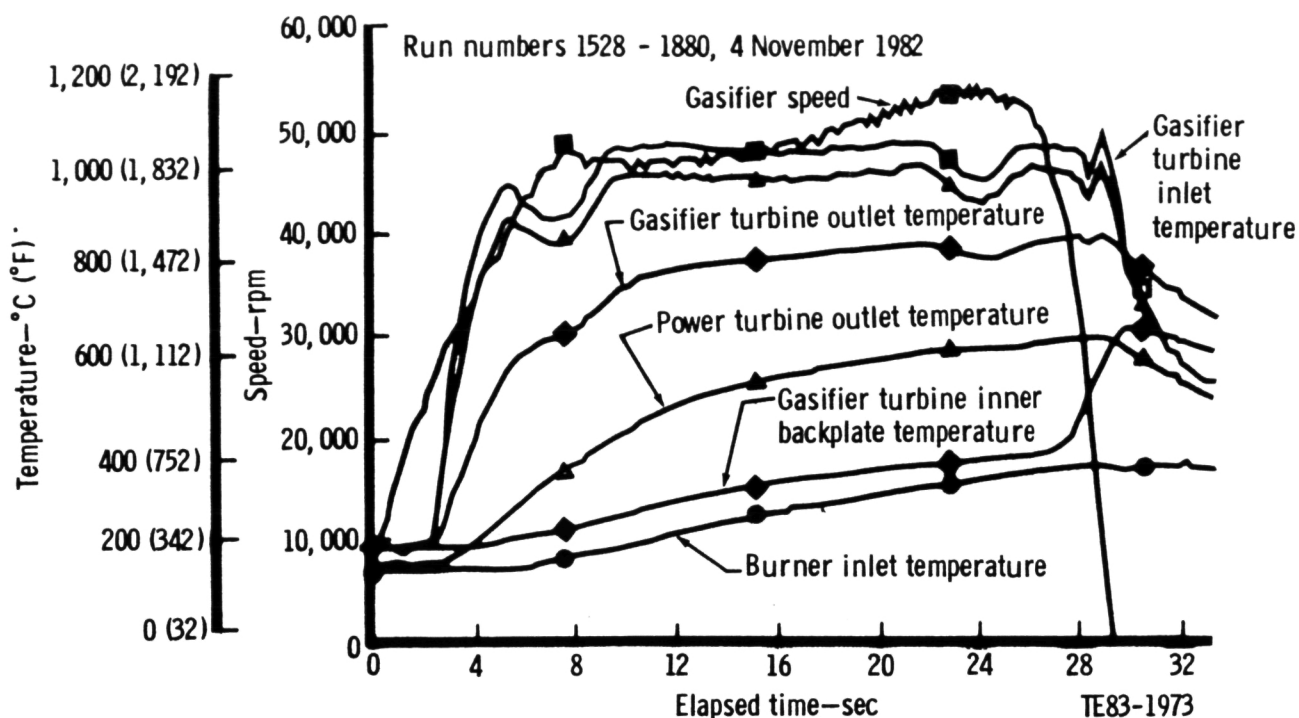


Figure 10. Start transient, BU3.

currence of rub.

Disassembly revealed that the gasifier turbine rotor did in fact rub the backplate at the inner diameter. There was a light rub at the exducer region as well. A subsequent thermal transient stress/strain analysis showed that the backplate would transiently distort by coning in at the inner diameter.

#### BU4 Test

This build incorporated a modified gasifier turbine inner backplate dimensionally modified to accommodate transient thermal distortion without physical contact with the rotor. Rub pins were also restored, using platinum in the hot section to obtain a very abrasible material. Testing goal for this build was to establish stabilized operation at 60% speed. A plot of transient parameters is shown in Figure 11.

Based on previous experience, the starter was maintained on for 40 sec to preheat parts. This allowed a greater portion of the turbine inlet energy to be applied to the thermodynamic expansion process (rather than to heating up parts). The engine reached governing speed (set at 58% for this run) on the starter, requiring about 650°C (1200°F) TIT. When the starter was dropped, speed dropped momentarily but recovered as temperature was

increased. Governing speed was reached, and TIT fell to about 960°C (1760°F) TIT after 70 sec into the run. Shortly thereafter, TIT increased gradually to maintain speed, finally reaching a fuel flow limit that produced about 1004°C (1840°F) TIT, after which speed sagged sufficiently to cause an underspeed shutdown. A study of all transient data showed that at about 62 sec, the power turbine rotor had rubbed its backplate. Power turbine speed had been maintained at 10% speed with the dynamometer during all starts.

Disassembly revealed that the power turbine rotor to inner backplate rub had caused the backplate to rotate. This movement damaged a rope seal between the inner and outer backplates. The damage to the rope seal allowed a substantial leakage path from burner inlet pressure to power turbine inlet pressure. A light rub was once again seen at the gasifier turbine exducer. Subsequent performance analysis showed that an assumption of 3.6% leakage from burner inlet cavity into the power turbine correlated with the observed transient data.

A study of the rub pin dimensions in relation to cold dimensions showed that the power turbine inner backplate was moving axially (i.e., not coning) into the turbine. Further transient thermal analysis indicated that the upper backplate, upon which the inner backplate is located, was distorting to allow this interference.

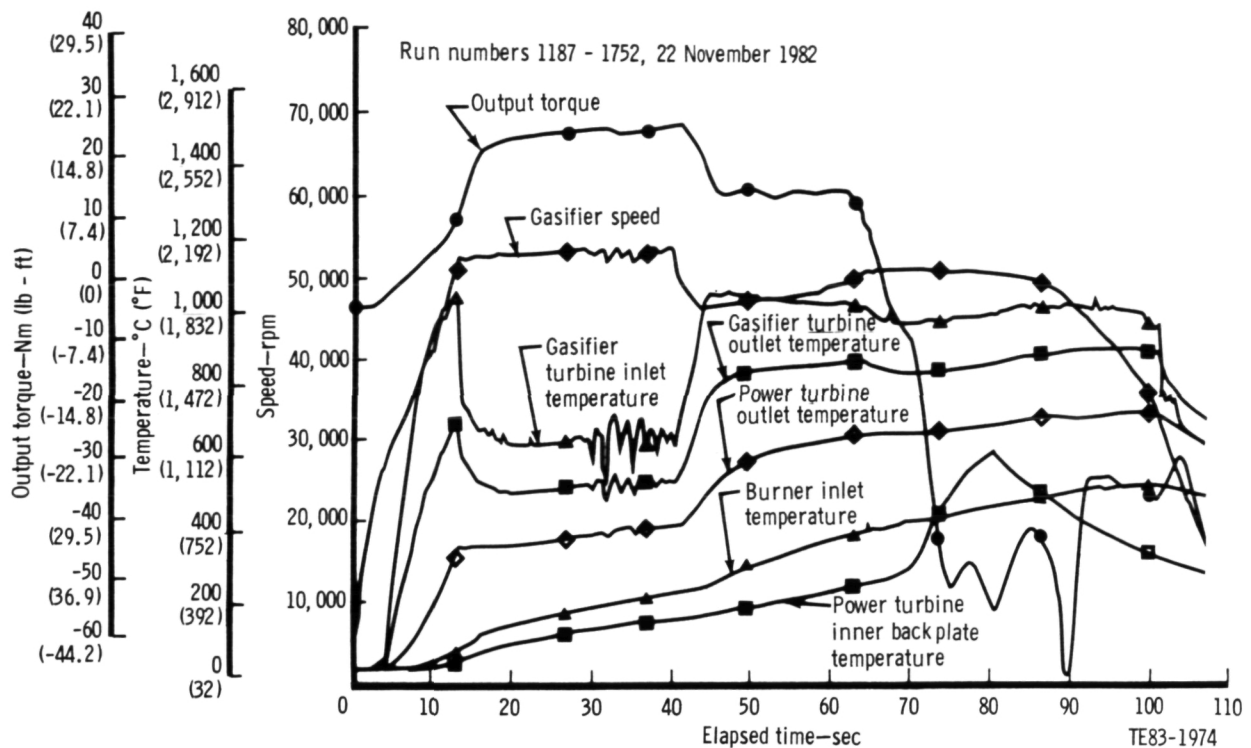


Figure 11. Start transient, BU4.

## BU5 Test

Previous testing had demonstrated the need for parts configuration modification to reduce the change in clearance during thermal transients. While this design work was under way, the engine was rebuilt with increased clearances. The gasifier turbine radial clearance was increased at the exducer to avoid the possibility of rub. Additional axial clearance was also added at the backplate. The power turbine radial clearance at the exducer was also increased.

The flow area of the power turbine was increased 10% by increasing the vane axial dimension. This increased axial dimension was distributed as additional axial clearance in the power turbine. This increased flow area was intended to compensate for the adverse effect of gasifier clearance on required TIT.

A typical start transient record from BU5 is shown in Figure 12. The engine was operating in the governing mode at about 760°C (1400°F) while on the starter. After starter cutoff, the control operated to re-establish governing speed. Thus, in a period of time between 45 sec and 88 sec, speed was first increasing at constant TIT to governing requirements, then TIT dropped to maintain governing speed at a minimum TIT of about 995°C (1820°F). At that point, the required-to-run TIT increased, reaching a limit-

ing fuel flow. At 88 sec, speed started to decay to an underspeed shutdown.

During the start that followed that of Figure 12, speed decayed rapidly after starter drop. A borescope inspection at that time showed a broken ceramic seal platform at the point adjacent to the power turbine exit, where it forms part of the flow path. The ceramic part is not rigidly connected to the power turbine scroll but is connected by a loose coupling, sealed with piston rings. A post-test analysis showed that the piston ring end gap was not sufficient to accommodate ring thermal expansion at the temperature level achieved on BU5. This allowed the piston ring to expand and overstress the ceramic part.

It is not clear exactly when this failure occurred, other than presumably at temperatures higher than heretofore obtained. Higher flow-path temperatures at the piston ring station did occur at the end of the run shown in Figure 12 and in the subsequent run. A crack that opened during a run would leak burner inlet air to the power turbine exit position. However, no clear evidence of a change in leakage is apparent in the test data.

## Performance

The testing previously described shows an operating characteristic common to the last three builds. During the start, the engine accelerates to governing speed, then re-

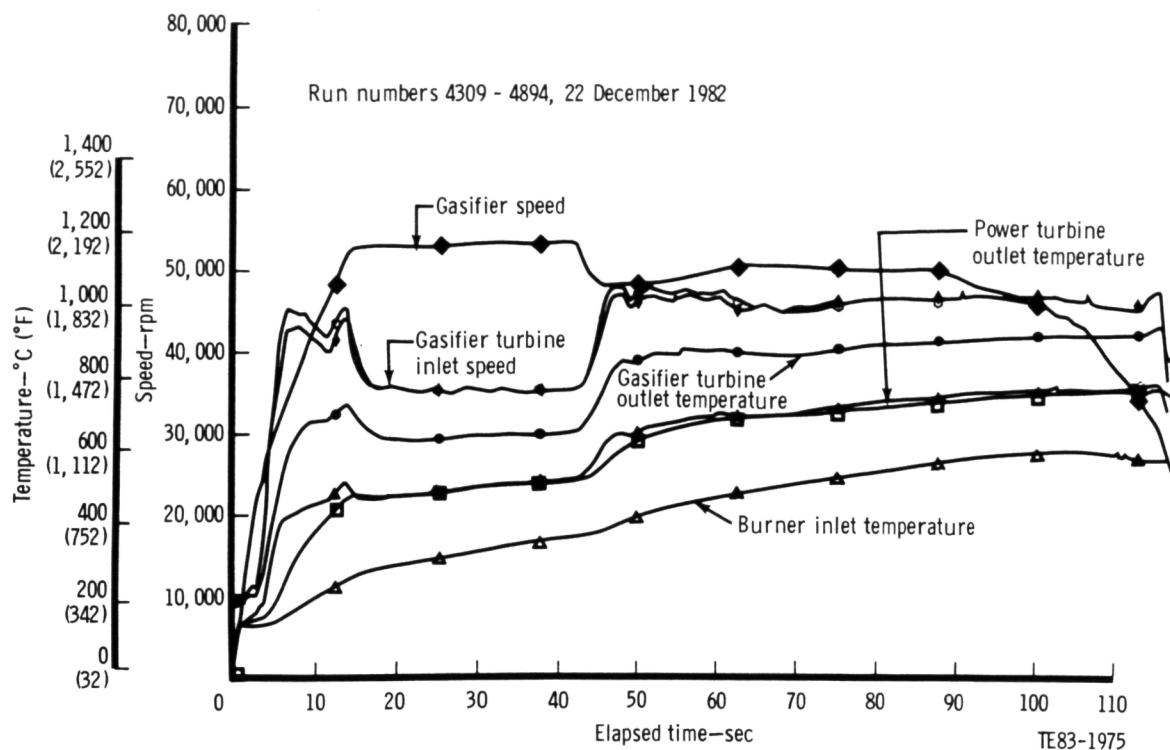


Figure 12. Start transient, BU5.

duces fuel flow (TIT) to the level required to maintain that speed. Then, after a short time, fuel flow rises gradually to maintain governing speed. It eventually reaches the control limit, whereupon rotor speed decays, leading to an automatic underspeed shutdown. The latter operation is abnormal and is probably the result of thermal effects producing component inefficiency, air leakage, or mechanical drag.

Mechanical drag, or rub, has played a major role in the test results. During the test of BU3 (see Figure 10), the temperature response (from rub on the gasifier turbine inner backplate) appeared 3 sec after minimum TIT was recorded. It is reasonable to believe that the drag began at the minimum recorded TIT point and was the cause of the shutdown.

During the test of BU4, the power turbine rub opened a leak path for air to bypass the combustor and gasifier turbine. It is clear from the data recordings of dynamometer torque (see Figure 11) that rub started at about 62 sec, whereas minimum TIT occurred at 70 sec. Seal damage allowing leakage most likely occurred at the time the TIT

was increasing to maintain governing speed.

Thermodynamic engine cycle calculations were done with BU4 data in an attempt to confirm and quantify leakage. Certain operating points that exhibited thermal and speed stability and also defined conditions before and after failure were chosen. Rig-test component performance maps were used. A transient heat loss allowance was used to match the test data transient temperature measurements. The cycle calculation was executed to obtain the best fit to the actual data recorded. The results of the calculations indicated that a higher level (+3.6%) of power turbine leakage existed after the rub. Sensitivity studies showed that this amount of leakage change requires 55°C (100°F) increase in TIT to maintain speed. While TIT did increase by 55°C (100°F), the control system fuel flow limit was reached at that point and it is thus uncertain whether the engine would have continued with a modest further increase in TIT.

BU5 was tested near the end of the reporting period, and performance analysis of the data had not yet been completed.

## IV. GASIFIER TURBINE DEVELOPMENT

### 4.2 GASIFIER TURBINE MECHANICAL DEVELOPMENT—MOD I, METAL SCROLL

Gasifier turbine scroll development effort during this reporting period involved evaluation of the rotor-to-scroll clearance during engine development testing in the transient start-to-idle speed range. A total of five engine builds were made in this period. In general, the engine accelerated satisfactorily, stabilized at idle speed, and then experienced a speed decay. Rub occurred between the gasifier rotor and the scroll and inner backplate on BU2 and BU3 and between the power turbine rotor and inner backplate on BU4. The rubs occurred approximately 20 sec to 30 sec after reaching idle speed, which is 65% gasifier rotor speed. The cause of the rubs fell into two general categories: (1) insufficient scroll hold down load and (2) transient thermal deflection of scroll components.

Following is a more detailed description in build sequence of the test results with respect to rotor rub and the corrective action taken.

#### BU2 Gasifier Scroll and Backplate Rub

Teardown inspection of the engine showed indications of light rub on both gasifier and power turbine shrouds and heavy rub on the gasifier turbine inner backplate, as shown in Figure 13. In addition to the rub, approx-

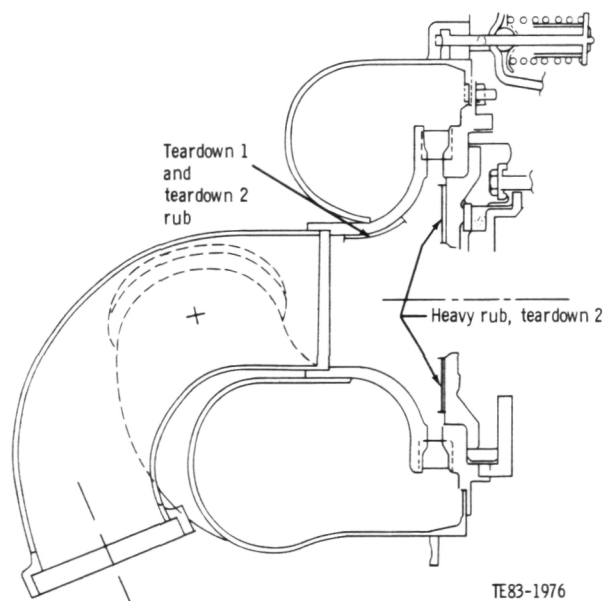


Figure 13. BU2 gasifier turbine rub areas.

imately 1 mm (0.039 in.) of the gasifier turbine rotor blade tips were missing, and the ceramic vanes in both turbines failed. The failure sequence could not be positively established due to damage of the relevant detail parts. However, high confidence is placed in the theory that the most likely primary failure mode is a gasifier rotor blade tip fatigue failure induced by heavy rub with the shroud and/or backplate. It was further concluded that the ceramic vane failures were secondary and were caused by the impact of the rotor blade tips.

The locus of the rub indications suggested scroll tilt with respect to the scroll cross-key support. A subsequent review of the scroll and scroll support structure loads was initiated. The review revealed that the scroll loading was greater than design loads and the scroll support required additional stiffness to react the load.

An interim design, which allowed the engine to run safely at up to 65% gasifier rotor speed, was incorporated in BU3. This design increases the scroll hold down force from 11.8 kg (26 lb) per spring to 23.1 kg (51 lb) and adds a support ring to provide increased support for the scroll assembly.

#### BU3 Gasifier Inner Backplate Rub

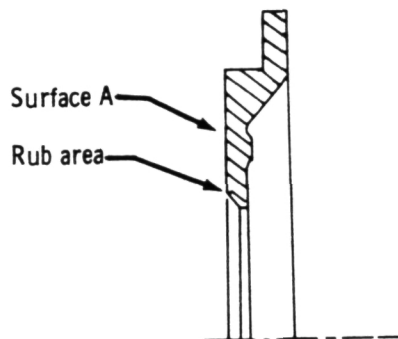
The gasifier turbine was self-sustained at idle speed for approximately 28 sec, followed by a rapid reduction in speed and eventual engine shutdown. The thermocouples added in this build on the back face of the inner backplate to detect rub indicated a sharp increase in temperature prior to the speed drop off. Teardown inspection revealed a rub between the gasifier turbine inner backplate and the gasifier rotor. The rub pattern on the inner backplate was restricted to a 360-deg face rub at the inside diameter, as shown in Figure 14. There was no indication of scroll tilt.

Since the build clearance between surface A of Figure 14 and the rotor was constant (0.6 mm [0.025 in.]), the rub pattern indicated the problem was one of transient thermal deflection rather than thermal growth or tilt. A transient heat transfer analysis showed that the backplate coned 0.5 mm (0.021 in.), 28 sec after fire-up, confirming the theory. This result is shown in Figure 15.

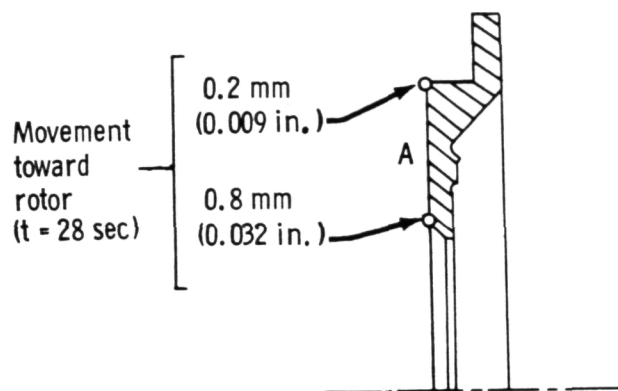
To provide transient clearance during future operation, surface A of the backplate design was modified to incorporate a taper. Thus, when thermally distorted, surface A will be essentially flat relative to the rotor backface.

#### BU4 Evaluation of Tapered Gasifier Backplate

The tapered gasifier turbine inner backplate was evaluated during testing of engine BU4. The gasifier rotor ac-



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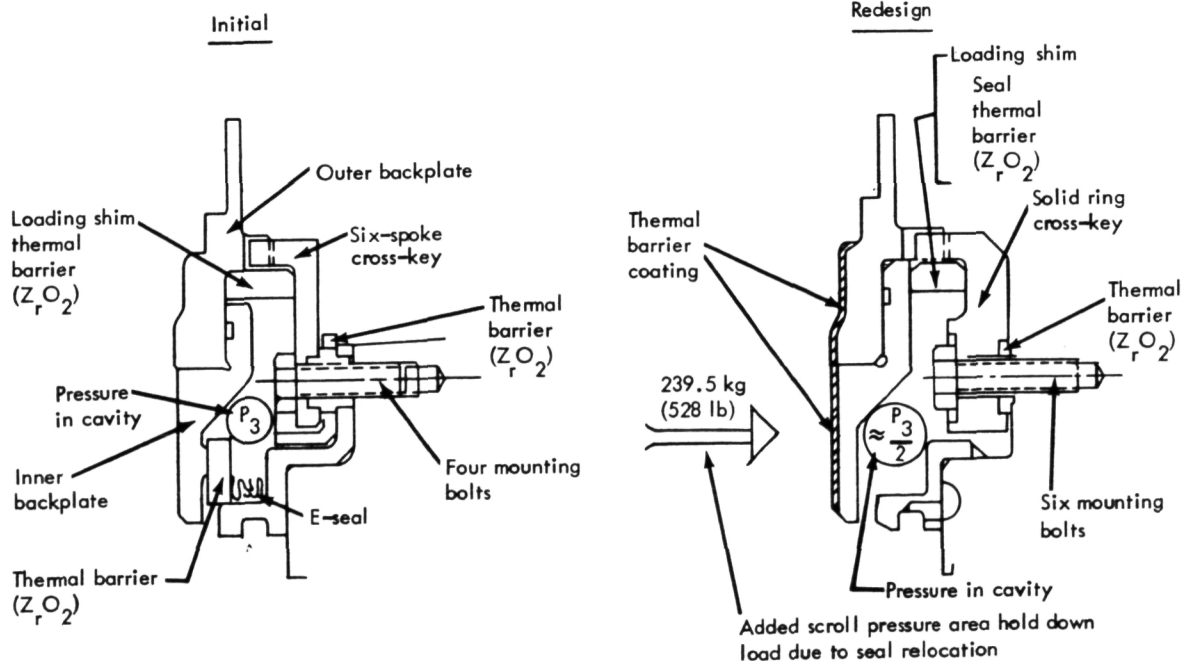
Figure 14. Gasifier turbine inner backplate—rub area.

celerated satisfactorily to idle speed, self sustained, and stabilized for a short period. Then speed decayed, and the run was terminated. There was no gasifier inner backplate temperature indication of rub and no indication of backplate rub on teardown. In fact, rub pin measurement after testing confirmed that the gasifier backplate coned the predicted amount and also translated axially. The cause of run termination was found to be rub of the power turbine backplate (see Section V).

Figure 15. Gasifier turbine inner backplate—transient deflection.

### Redesign

A layout was started that not only addresses the transient thermal deflection problem but also the scroll hold down problem for both metal and ceramic scrolls. A sketch of the present and redesigned gasifier scroll support system is shown in Figure 16. The salient features of the redesign are listed in Table III. The gasifier turbine scroll support system that will be incorporated into engine BU6 (see Figure 17) is being redesigned.

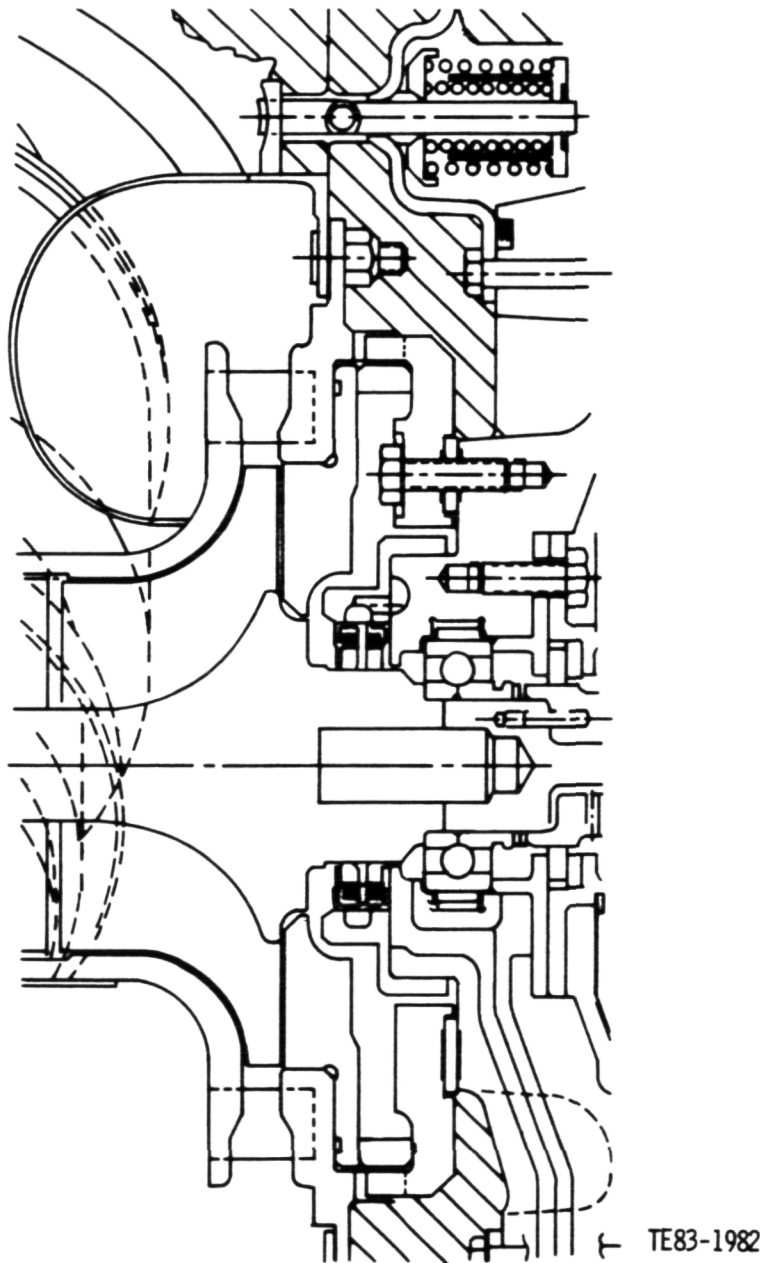


TE83-1981

Figure 16. Scroll mounting system comparison—present versus redesign.

**Table III.**  
**Redesign features and benefits.**

Feature	Benefit
1. Seal relocated outboard	1. Reduces pressure behind inner backplate and increases pressure area force holding the scroll against the cross-key support
2. Solid ring cross-key support	2. Increases stiffness, which reduces deflection under load
3. Increased number of support mounting bolts	3. Uniform distribution of load from scroll cross-key support into gasifier turbine bearing support
4. Increased inner backplate o.d. to be in load path between outer backplate and shim	4. No translation of inner backplate due to transient thermal deflection coning of outer backplate and scroll
5. Thermal barrier coating on scroll and outer backplate flow-path surfaces	5. Reduces transient thermal deflection, which allows reduced running clearances, resulting in improved efficiency



**Figure 17. Gasifier turbine—redesign scroll support system.**

## V. POWER TURBINE DEVELOPMENT

### BU2 POWER TURBINE SCROLL AND BACKPLATE RUB

A design modification similar to that for the gasifier turbine scroll (see subsection 4.2) was incorporated in the power turbine scroll and supporting structure. This design increases the scroll hold down force from 11.8 kg (26 lb) per spring to 23.1 kg (51 lb) and adds a support ring to provide increased stiffness to the scroll support structure.

### ANALYSIS OF BU3 POWER TURBINE BACKPLATE

Since the gasifier backplate had rubbed during testing of BU3 (see subsection 4.2), the power turbine inner backplate was also analyzed for transient thermal deflection. The results showed a maximum coning of only 0.17 mm (0.007 in.) at 26 sec after fire-up, as shown in Figure 18. Because the build clearance between the backplate and rotor is 0.5 mm (0.020 in.) minimum and there was no indication of rub on previous builds, no change was made to the power turbine inner backplate for BU4.

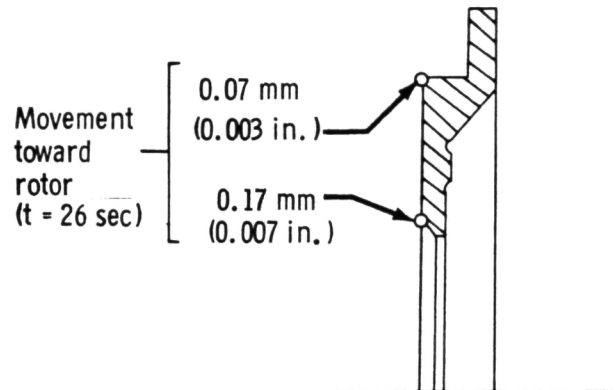
### BU4 POWER TURBINE INNER BACKPLATE RUB

The power turbine system showed rub between the rotor and inner backplate inside diameter similar to the gasifier inner backplate rub during BU3. During running, the power turbine backplate thermocouples had indicated that rub had occurred. On teardown inspection, the rub pin measurements indicated that the power turbine backplate translated axially (not by coning, as previously experienced on the gasifier backplate). The power turbine rub did not directly cause the gasifier rotor speed decay, since on this build the two rotors were not connected mechanically. Teardown inspection revealed, however, that the power turbine inner backplate ceramic rope seal was out of its groove and wedged between the inner and outer backplate. This resulted in an air leak into the power turbine scroll.

Since the power turbine inner backplate analysis done prior to this test indicated a very minimal amount of coning (0.1 mm [0.004 in.]), which did not explain the rub, and the rub pin measurements indicated the backplate translated, the transient heat transfer and deflection analysis was extended to the power turbine scroll assembly. The results showed coning of the outer backplate, which caused the inner backplate to translate, as shown in Figure 19. The sum of deflection due to coning, translation due to outer backplate coning, and thermal growth of support structure was sufficient to use up the build clearance

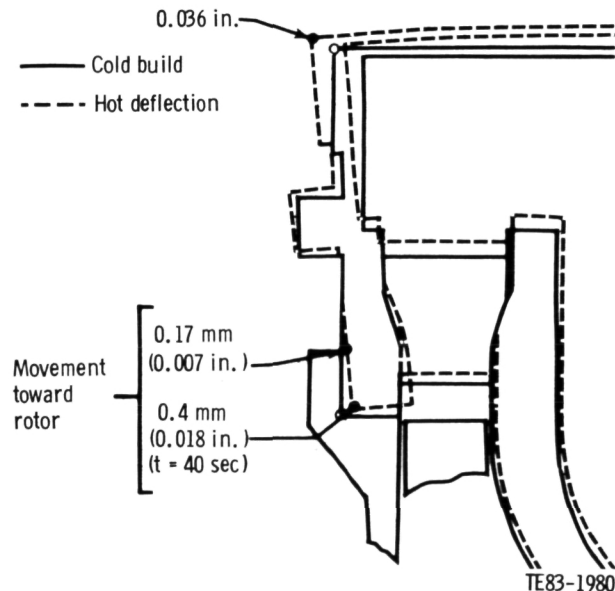
and cause rub.

The power turbine scroll support system design that will be incorporated into engine BU6 (see Figure 20) is being developed.



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Figure 18. Power turbine inner backplate—transient deflection.



TE83-1980

Figure 19. Power turbine scroll assembly—transient deflection.

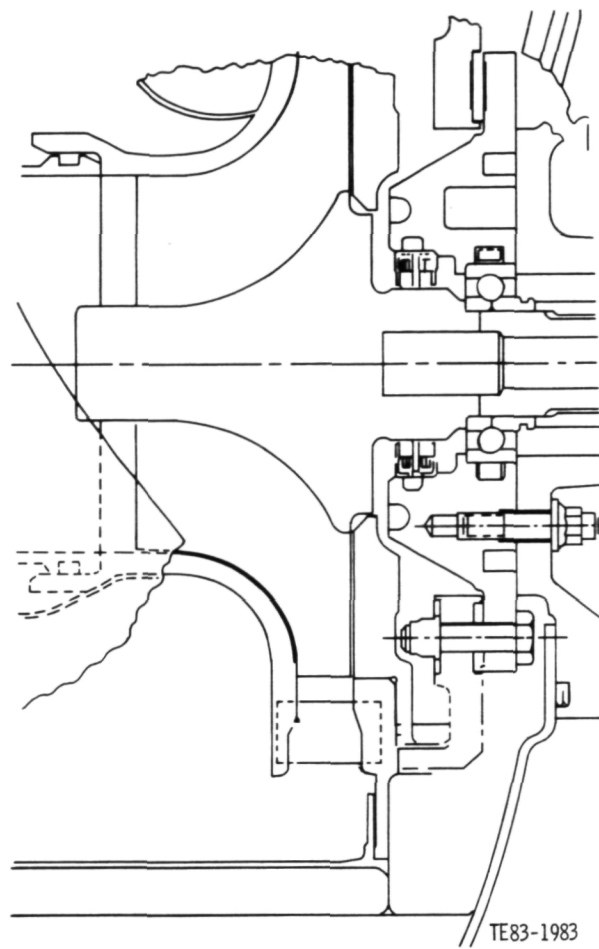


Figure 20. Power turbine—redesign scroll support system.

## VII. REGENERATOR DEVELOPMENT

Regenerator development activity during the preceding period concentrated on proof testing regenerator hardware for the first engine build. This work indicated that the following additional development was required: (1) improve heat transfer effectiveness by modifying regenerator disk airflow distribution and (2) reduce regenerator system leakage. Effort during this reporting period has addressed these problem areas and is reported here. In addition, regenerator system performance during the early engine testing is summarized.

### FLOW DISTRIBUTION TESTING

To maximize regenerator disk performance (maximum effectiveness and minimum pressure drop), it is necessary to match the gas side and air side flow distribution in the disk. Flow models of both the engine gas side and air side configurations that model the actual Reynolds and Mach number conditions of the disk allow room temperature testing at simulated engine conditions.

Testing of the initial engine configuration resulted in a calculated degradation in regenerator effectiveness of 10.6%, due primarily to poor distribution characteristics of the air side. A series of eight modifications were tested, the first two of which were reported in the preceding semi-annual report (Ref 1). The second of these two modifications successfully improved the disk effectiveness, but at the expense of increasing the pressure drop from 0.5% to 1.5% (see Figure 21). The addition of the side air inlet at the disk perimeter (Mod II, Figure 21) was then combined with the original flow path, and various flow splits (Mods III-VIII) were tested to tailor a configuration meeting requirements of matching both distribution and low-pressure drop.

Mod VIII, shown in Figure 22, incorporated a 50-mesh screen and flow trip at the upper flow entrance and created a manifold effect through use of a 4½% porous plate installed inside the regenerator cover. At simulated 100% power conditions, this design gave an estimated effectiveness that was within 0.2% of uniform flows and a measured pressure drop of 0.56% (versus 0.5% for the baseline). Testing was expanded to the idle and 13.4 m/s (30 mph) operating conditions to check performance at these flow conditions. The resulting data, summarized in Figure 22, indicated that only at idle did the disk effectiveness deviate significantly from uniform flow characteristics. Figure 23 shows plots of the circumferentially averaged velocity profiles for the idle and 13.4 m/s (30 mph) condition (air side and gas side). The engine regenerator cover was reworked for engine BU3 to incorporate the

Mod VIII changes, as shown in the photo sequence of Figures 24, 25, and 26.

### REGENERATOR SYSTEM LEAKAGE

The first sets of regenerator hardware exhibited system leakage levels, as shown in Figure 27, that were acceptable for initial engine testing, but too high for later engine performance evaluations. The objective of the analysis of system leakage characteristics was to identify and quantify the individual leakage sources to establish development goals for reducing system leakage.

Leakage was categorized into five areas—all of which could be based on analytical results and/or rig testing. Figure 28 illustrates the magnitude of these individual sources for the initial engine hardware set. Each is discussed in the following:

- **Disk carry-over.** These calculated losses are a function of disk speed and tradeoff against the changes in effectiveness. Minor improvements may be possible through further optimization of operating speeds and the inclusion of seal crossarm porting to capture some of the normal carry-over losses.
- **Wearface.** A major factor in leakage, which cannot be measured directly but is found by subtracting other leakages from total rig measured leakage. This loss is the summation of rim and crossarm leakage of both inboard and outboard seals and is influenced by type of wearface joint, flatness, surface damage, and distortion.
- **Inboard leaf.** Leaf leakage rig measurements of inboard seal leaves are scaled to engine operating conditions to define these leakages. Primary loss sources are leaf joints, corner miter joints, and leaf deformation (waviness) due to yielding at high operating temperatures. Elimination and/or improved joints and floating leaf structures are being studied to reduce these losses.
- **Outboard leaf.** Rig-measured leaf leakages are scaled to engine conditions. Observation of leaf operation shows that the majority of leakage occurs at leaf joints and corner leaf miters. Elimination or reduction of the number of joints is being pursued in reducing this leakage.
- **Disk.** Investigation of the physical characteristics of the initial AGT 100 code 9461 (CGW) aluminum silicate disks revealed abnormally high "through wall" leakage due to wall porosity. Comparable disks used in the Allison CATE program exhibited through wall leakage levels 60%-75% lower than the AGT 100

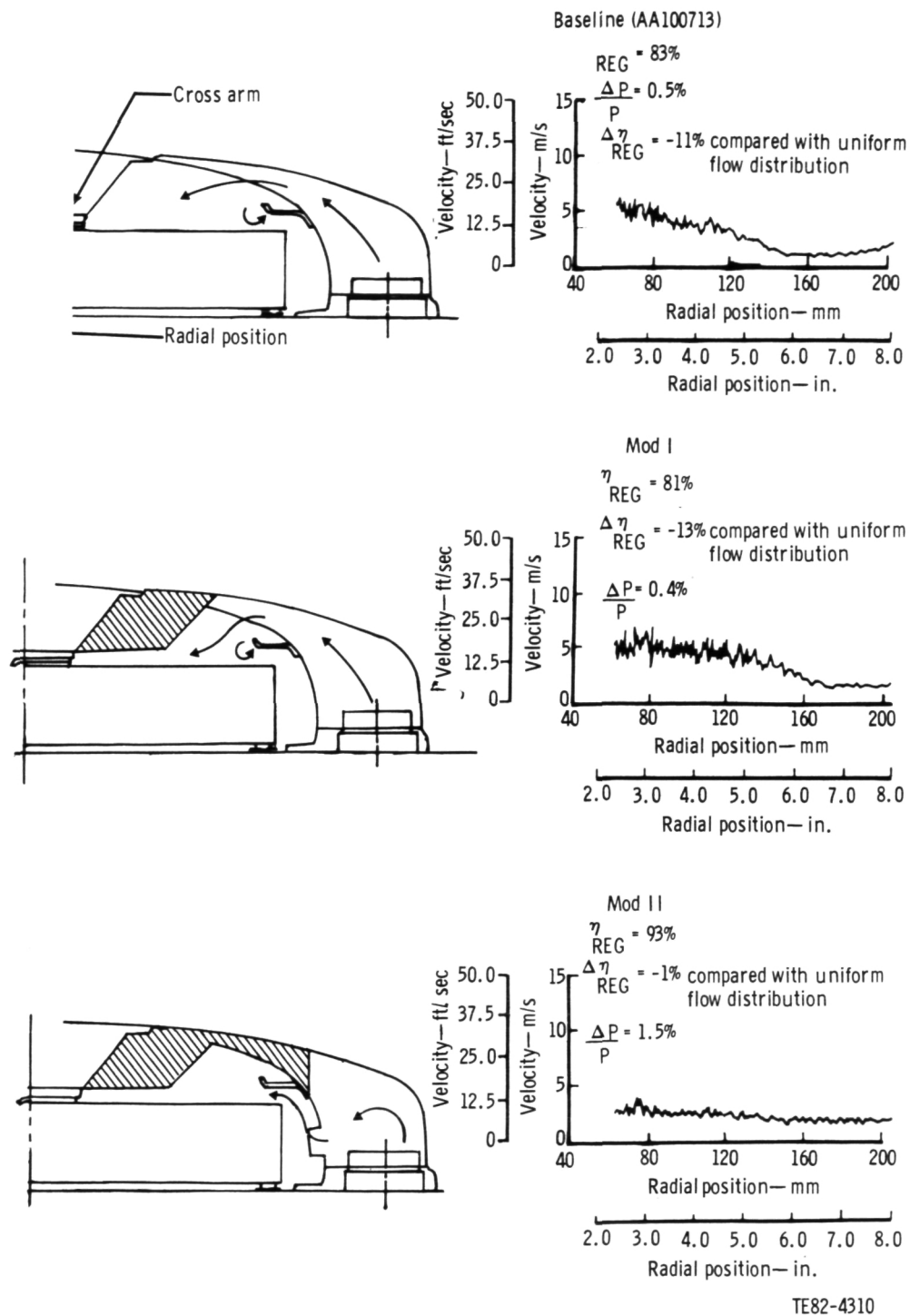
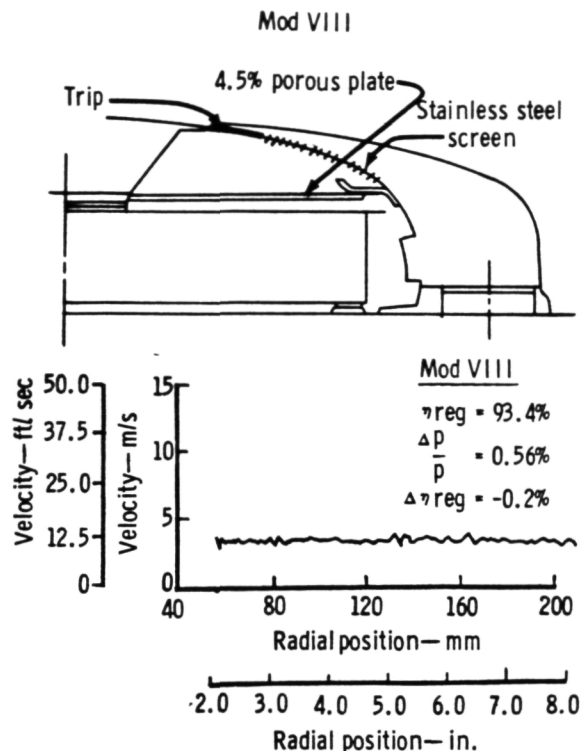


Figure 21. Regenerator air side flow distribution testing.



Effectiveness data summary

Simulated engine operating condition	With uniform distribution	With Mod VIII
100%	93.6%	93.4%
48.3 m/s (30 mph)	97.7%	97.4%
Idle	98.5%	97.1%

TE83-1984

**Figure 22. Mod VIII flow model.**

disks. An improved leakage specification has been negotiated with the supplier and AGT 100 disks with a reduced through wall leakage of  $17.61 \mu\text{g/sec-mm}^2$  ( $2.5 \times 10^{-5} \text{ lb/sec-in.}^2$ ) will be rig and engine tested early in 1983.

The immediate goal is to demonstrate system leakage levels approaching the Mod I goals (see Figure 27) with the seal and disk improvements to be tested during the next reporting period.

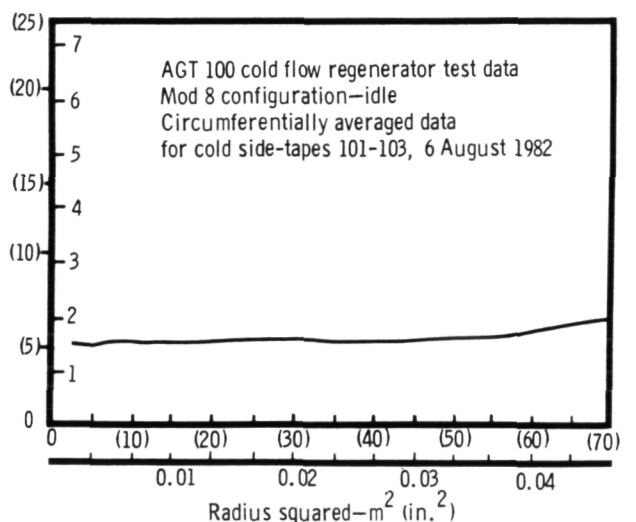
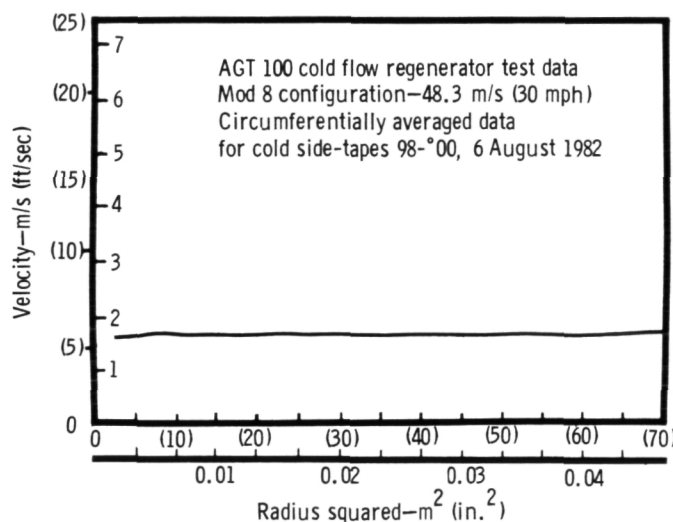
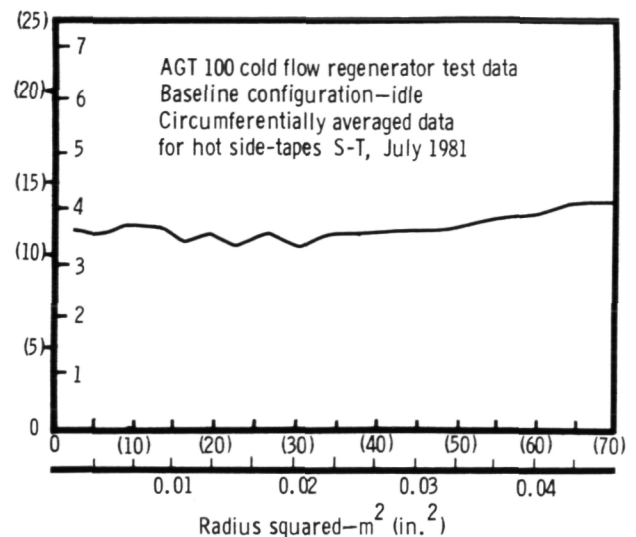
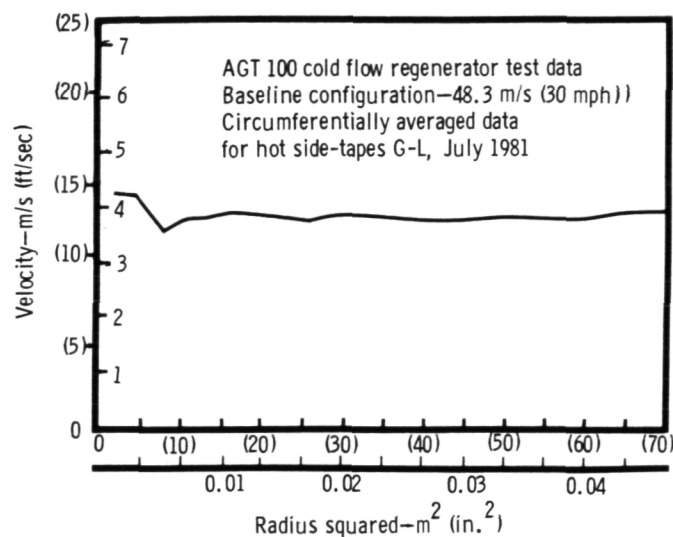
## ENGINE TEST SUPPORT

During engine testing, regenerator data have been obtained on environmental temperature effects and the effect of upstream hardware failures on disk damage. The ceramic regenerator seal platform/exhaust duct incorporates a flexible mounting in the engine between a compliant (Vitm<sup>®</sup>) gasket and a silicone O-ring, as shown in Figure 29. Using temperature sensitive paint, seal platform temperatures were recorded during engine operation to determine whether the seal platform operating temperatures were compatible with the Vitm and silicone parts it contacts. The results, shown in the photos in Figures 30 and 31, indicate surface temperatures of  $215.5^\circ\text{C}$ - $232^\circ\text{C}$  ( $420^\circ\text{F}$ - $450^\circ\text{F}$ ) for the O-ring installation and less than  $215.5^\circ\text{C}$  ( $420^\circ\text{F}$ ) for approximately 90% of the compliant gasket contact area, with the remaining 10% in an environment of less than  $282.2^\circ\text{C}$  ( $540^\circ\text{F}$ ). Post-run inspection of these parts showed no degradation. The isotherm plots in Figure 31 also indicate the temperature gradients through the ceramic duct during engine operation up to  $815.5^\circ\text{C}$  ( $1500^\circ\text{F}$ ) gas temperature and illustrate the satisfactory thermal barrier that the ceramic foam layer is providing around the rim of the ceramic duct. The thermal environments of the regenerator components will continue to be monitored with thermal paint and/or thermocouples until all engine operating conditions have been investigated.

During tests of BU5, interference between the metal power turbine coupling/piston rings and the ceramic duct entrance resulted in the fracture of the ceramic duct due to excessive hoop stresses from the interference. Calculations verified an interference condition with the engine parts at elevated gas temperatures; the coupling was reworked to eliminate this problem (see Section II, BU5).

During testing of BU2, there was a failure of the ceramic stator vanes and metal rotor tips. Debris from the failure exited through the gas side of the regenerator disk with only minor degradation of the disk surface. Inspection of the disk hot face revealed damage (up to 0.4 mm-0.5 mm [0.015 in.-0.020 in.] deep) to the flow passage radial separators. There were no areas of the disk face in which the number of damaged separators was sufficient to warrant removal of the disk from the engine, and engine testing is continuing with this disk.

\*Vitm is a registered trademark of the DuPont Company.



(a)

(b)

TE83-1985

Figure 23. Circumferentially averaged flow distribution data for regenerator at (a) 30 mph and (b) idle.

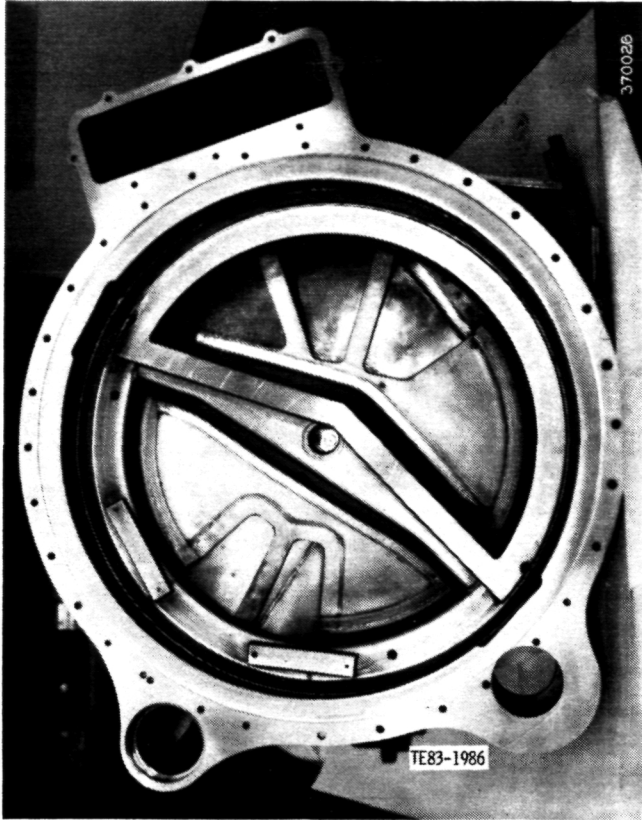


Figure 24. Regenerator cover before rework.

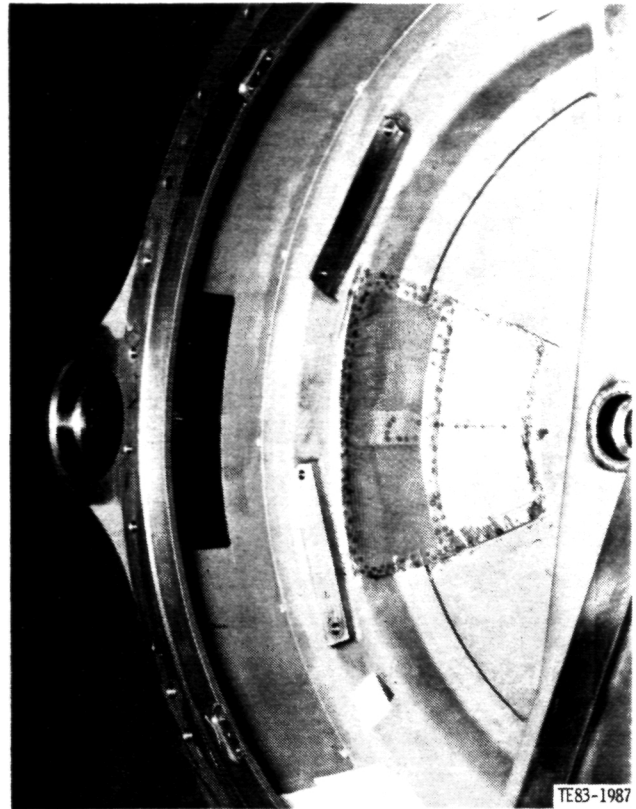
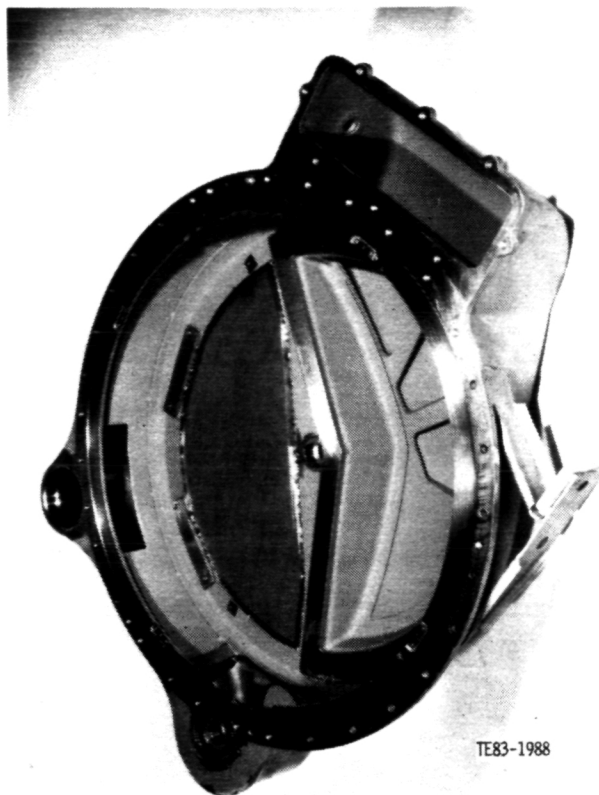
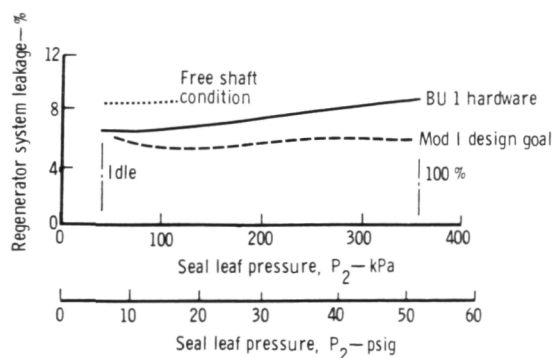


Figure 25. Rework of regenerator cover showing additional air inlet and trip screen cover of original inlet windows.



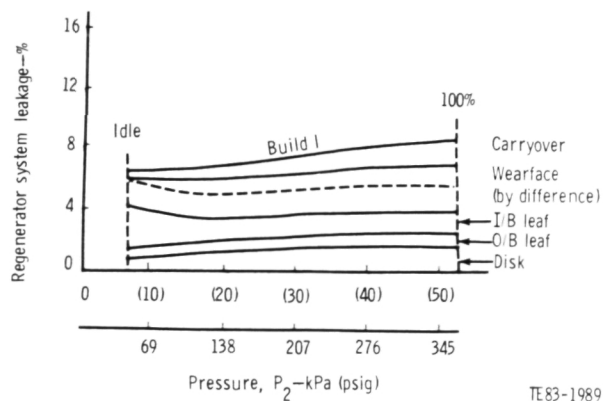
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Figure 26. Completed rework of regenerator cover to improve air side flow distribution.



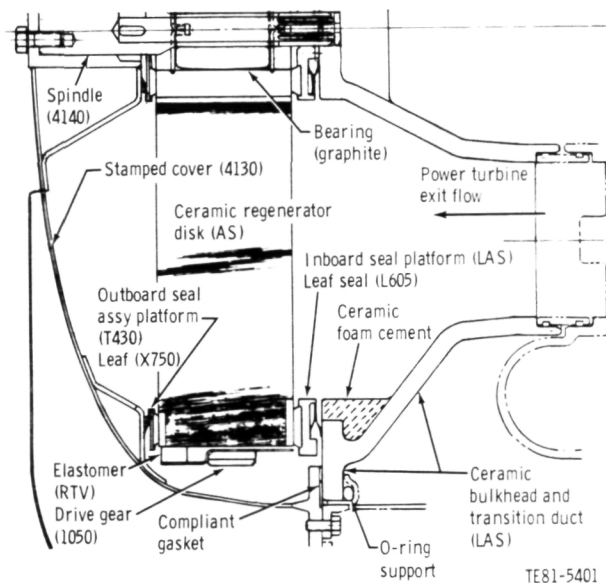
TE82-4320

Figure 27. Regenerator system leakage for BU1.



TE83-1989

Figure 28. Breakdown of regenerator leakage losses for AGT 100 BU1.



TE81-5401

Figure 29. Regenerator seal platform/exhaust duct installation.

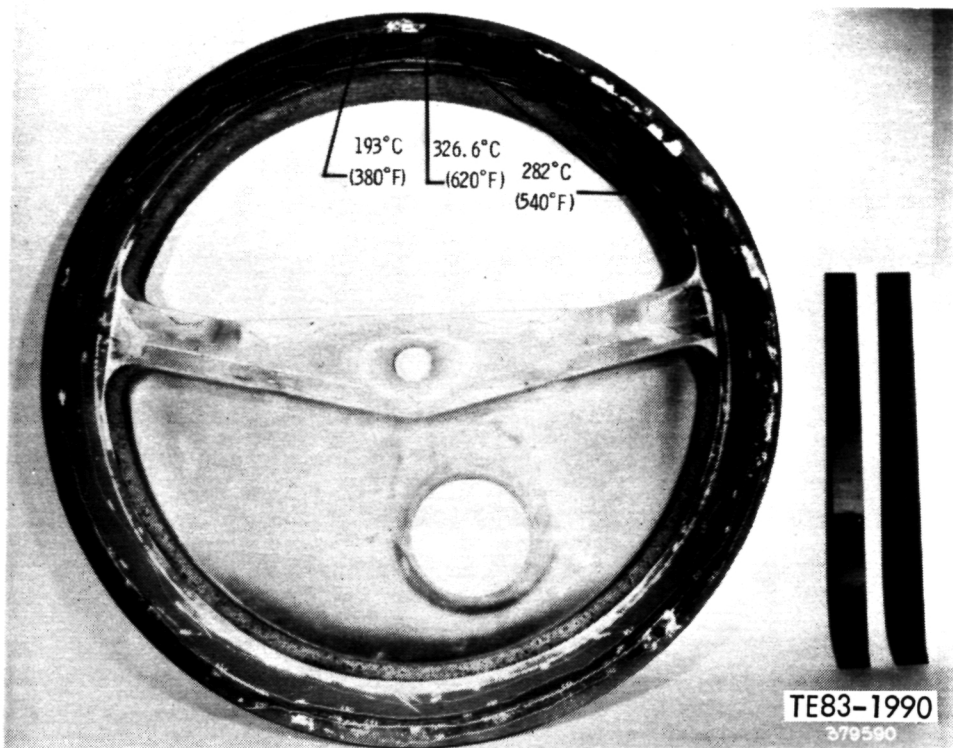


Figure 30. Ceramic seal platform isotherms after teardown 5—disk side.

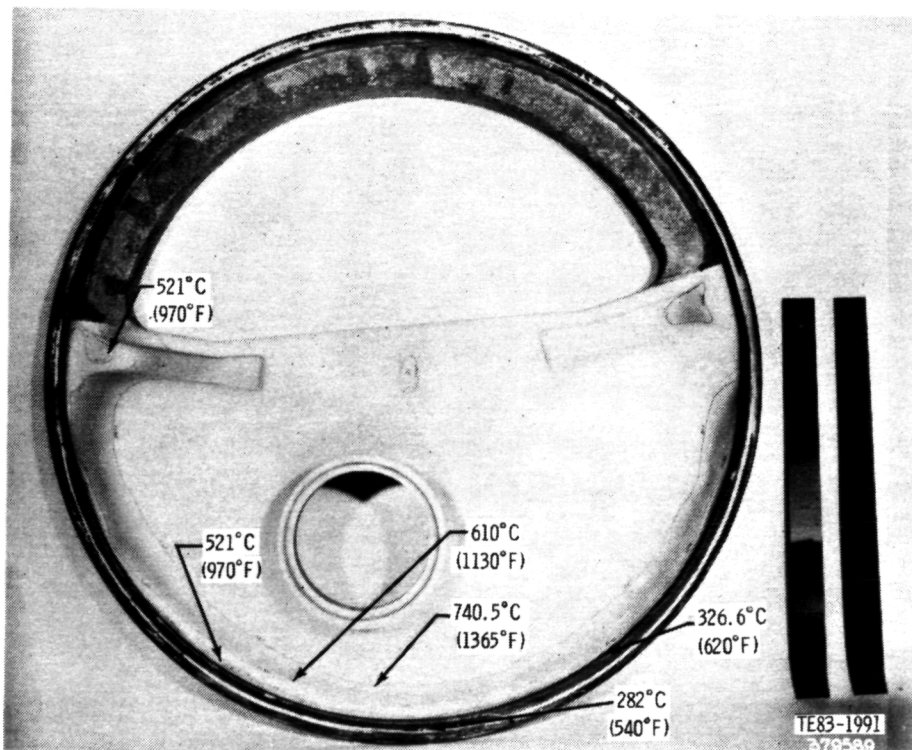


Figure 31. Ceramic seal platform and exhaust duct isotherms after teardown 5—power turbine (inboard) side.

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## VIII. SECONDARY SYSTEMS

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### 8.2 GEARBOX AND POWER TRANSFER

#### Power Transfer Clutch

The power transfer clutch is a cone clutch engaged by supply oil pressure acting upon a piston to move the clutch cone axially toward the mating cone surface. Disengagement is provided by a Belleville spring pack.

During initial testing of the clutch, it was found that the clutch would not transmit the required torque at the available engine oil pressures. The maximum torque requirements are 26.2 N·m (232 lbf-in.) for braking and 18.5 N·m (164 lbf-in.) for power transfer at 482.6 kPa (70 lbf/in.<sup>2</sup>) oil pressure. The initial clutch transmitted only 16.9 N·m (150 lbf-in.) at 482.6 kPa (70 lbf/in.<sup>2</sup>) oil pressure. It was decided at this time to modify a second clutch to improve the torque transmitting capability of the unit.

A new clutch was designed to fit in the original envelope with a minimum of rework to the original clutch. The new clutch (see Figure 32) delivers oil through an added transfer tube to a second piston. This piston acts in conjunction with the original piston to provide twice the axial engagement force to the cone surfaces.

The additional force should permit the clutch to transmit more torque. Testing of this modified clutch is now in progress to qualify it for engine use.

#### Regenerator Drive

The testing of the regenerator drive unit was completed this reporting period, resulting in a unit that is acceptable and available for engine use. This unit was designed to replace the harmonic drive assembly which did not meet endurance requirements during its testing.

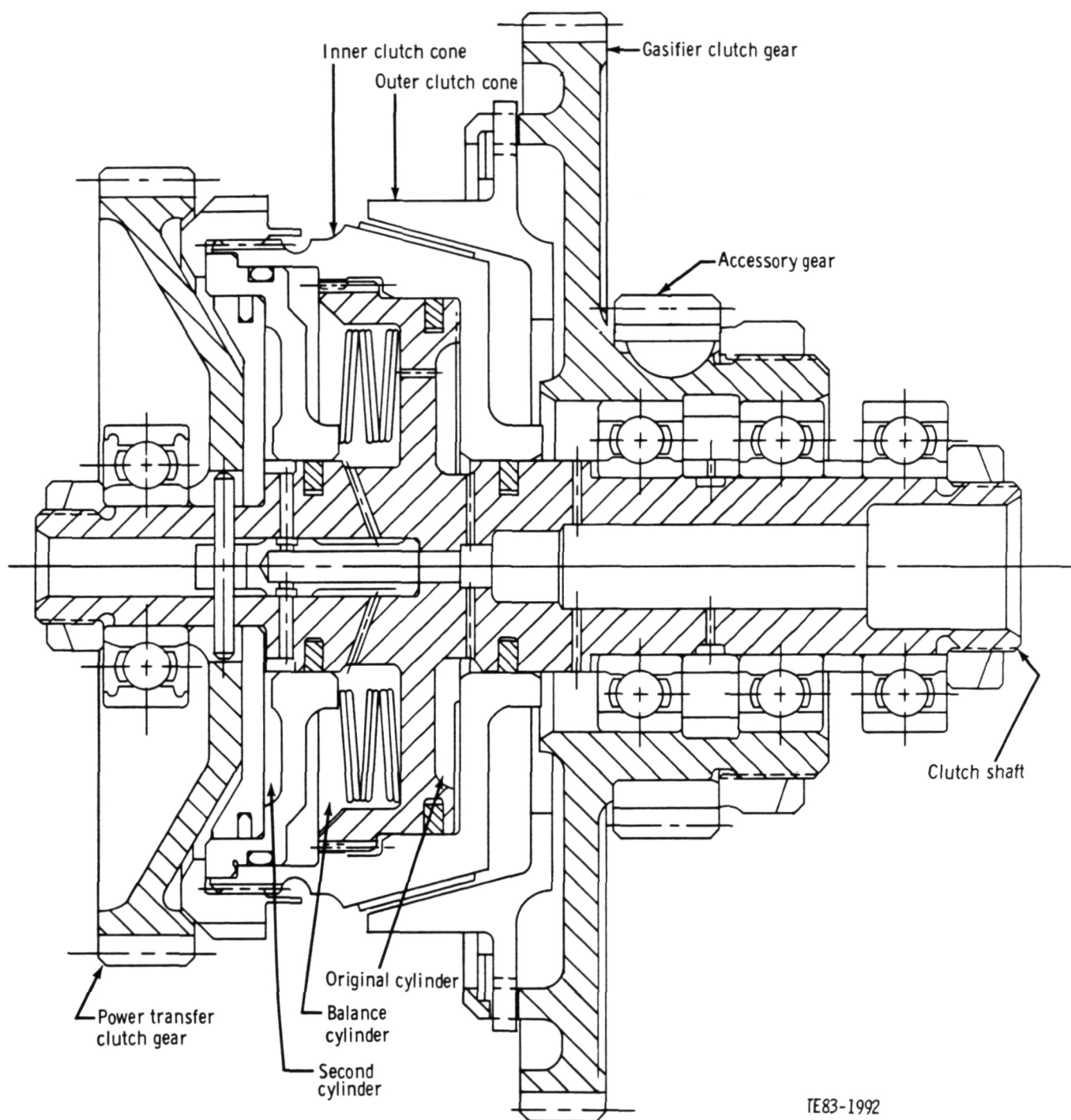
The replacement gearbox has undergone several refinements as a result of bench tests to meet endurance requirements.

The first regenerator drive unit demonstrated the soundness of the basic design by enduring 7 hr of testing. The testing was stopped when scoring of the pinion and counterbalance contact faces was discovered. The half-diameter contact face of the counterbalance had wiped the lubricating oil film from the pinion face. The metal-to-metal rotating contact allowed scoring and some metal removal from the surfaces.

The half-diameter contact face was replaced by a full-diameter contact surface on the counterbalance. This configuration encountered the same results due to lack of oil distribution to the interface area.

The next refinement included an oil dam in the shaft of the counterbalance. This allowed a layer of oil to build up in the shaft. A radial hole connected this passage to the interface area, allowing direct lubrication of contact surfaces. Also included were four radial oil slots in the face of the pinion. This modification produced improved endurance, but the surface wear of the contacting surfaces was still unsatisfactory for trouble-free engine use.

The final modification included a leaded bronze thrust washer between the pinion and the counterbalance. This washer has two radial oil slots per side. The oil slots were eliminated from the face of the pinion. This unit underwent 7 hr of testing, including more than 5 hr at 75% and 100% load. The contact surfaces showed no signs of degradation. Figure 33 shows the counterbalance, thrust washer, and pinion after testing. Based on these results, it was determined that testing was completed and the drive unit was acceptable for engine use.



TE83-1992

Figure 32. Power transfer clutch assembly.

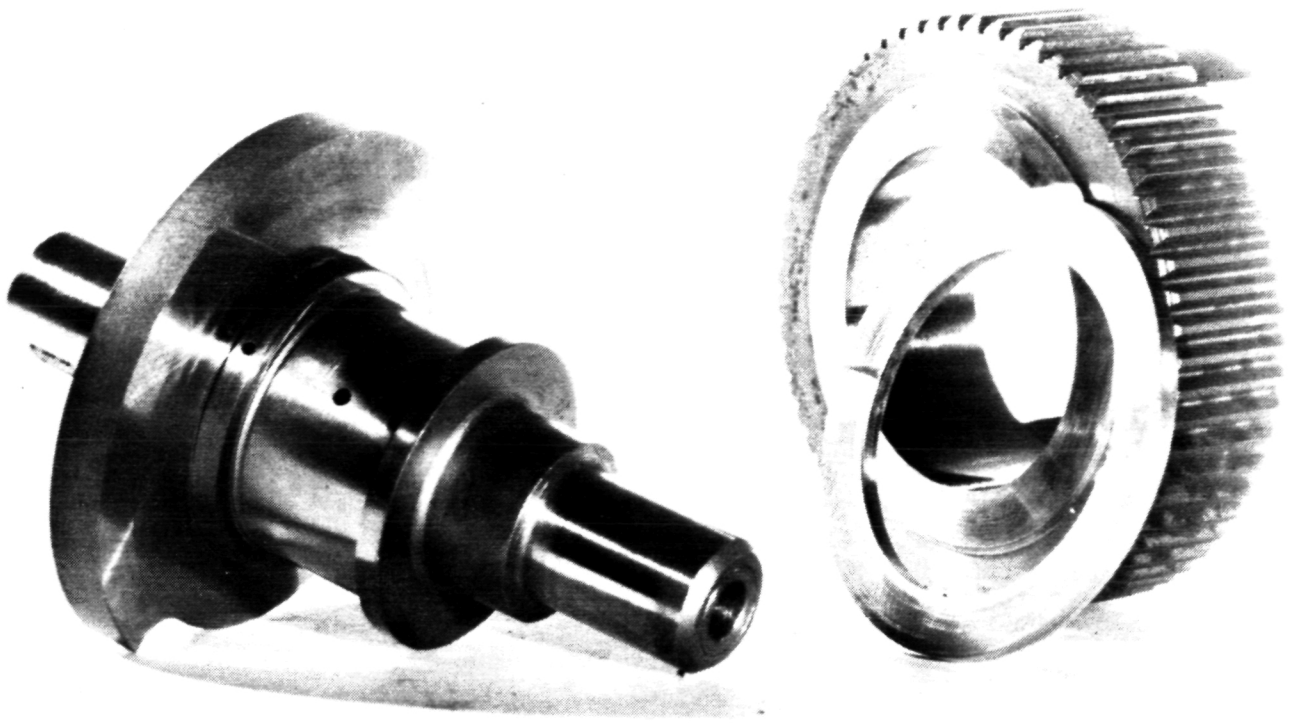


Figure 33. Regenerator drive counterbalance, thrust washer, and pinion.

## IX. MATERIALS DEVELOPMENT

### 9.1 THERMAL BARRIER DEVELOPMENT

The primary structural ceramic material in the reference power-train design (RPD) engine is silicon carbide. To obtain optimum engine performance it is necessary to operate at high temperature—in the range of 1288°C (2350°F). Since silicon carbide has a high thermal conductivity, steps must be taken to reduce heat transfer to the surrounding structures. It is necessary, therefore, to introduce thermal barrier materials in strategic locations to prevent excess heat loss from the engine and to maintain structure temperatures within acceptable operating ranges. Candidate thermal barrier materials need to have low conductivity, adequate strength, compatible thermal expansion coefficients, and the capability of being produced in proper shapes and sizes.

Carborundum Company (CBO) has embarked on a program to develop mullite as a thermal barrier. Allison has concurrently been working on the development of zircon-based materials. Previous work has shown that both material systems have very good thermal expansion compatibility with silicon carbide. Work during this period has focused on characterization of the necessary thermal properties required for mechanical design considerations. The following two subsections describe the progress to date in the development/evaluation of these materials.

#### CBO Effort

Research at CBO has been carried out in the  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$ - $\text{MgO}$  ternary oxide phase field. Materials have been produced from sol-gel prepared powders. These powders yield a two-phase material containing theoretically 59% mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) and 41% cordierite ( $2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$ ). Dense bodies (2.71 g/cm<sup>3</sup> true density, with 5% porosity) are the product of isopressing and sintering in air. Work has centered on thermal and elastic property characterization.

Table IV lists the thermal diffusivity of CBO mullite as a function of temperature. These data were obtained using a laser flash method at an outside vendor, Energy Materials Testing Laboratory (EMTL).

Table V lists the elastic properties for CBO mullite measured by a sonic modulus technique at the Allison materials lab. Poisson's ratio was calculated from the relation:  $\nu = E/2G - 1$ .

#### Allison Effort

Previous work to date has centered on the development of high-density zircon materials. Procedures have been established for the powder processing steps. Mate-

Table IV.  
Thermal diffusivity for CBO mullite.

Temperature		Thermal diffusivity	
°C	°F	mm <sup>2</sup> /s	(ft <sup>2</sup> /hr) x 10 <sup>-2</sup>
21	70	1.84	7.13
52	126	1.71	6.63
108	226	1.53	5.93
150	302	1.43	5.54
216	421	1.29	5.00
260	500	1.24	4.81
403	757	1.08	4.19
531	988	1.00	3.88
675	1247	0.93	3.60
770	1418	0.88	3.41
892	1638	0.85	3.29
1099	2010	0.80	3.10

rials have been produced that have excellent thermal expansion compatibility with sintered alpha silicon carbide;  $\alpha$  zircon = 5.0 mm/mm x 10<sup>-6</sup>/°C (2.7 in./in. x 10<sup>-6</sup>/°F), and  $\alpha$  SiC = 4.8 mm/mm x 10<sup>-6</sup>/°C (2.6 in./in. x 10<sup>-6</sup>/°F). Work during this period centered on obtaining the physical and mechanical property data necessary for design analyses.

The thermal diffusivity was measured by a laser flash method at EMTL. The data are listed in Table VI. These data will be utilized to compute thermal conductivity as a function of temperature.

Small zircon billets were prepared for MOR strength measurement. Strength was measured in four-point bending, at room temperature and 1000°C (1832°F), for bars with fully machined tensile surfaces. Table VII lists the most recent data as they compare with previous data. The most recent data are consistent with previous results. In most cases, fracture initiated from the surface. The strength at 1000°C (1832°F) was very satisfactory and illustrates the excellent strength retention character for the Allison zircon.

Young's modulus and Poisson's ratio were measured for the zircon material. Table VIII lists the values for Poisson's ratio and modulus as a function of temperature.

### 9.2 SILICON CARBIDE COMPONENT DEVELOPMENT

Efforts during this reporting period continued to focus on the fabrication, characterization, and qualification of silicon carbide components. Development activities at CBO on the gasifier rotor concentrated on translating the injection molding processing established for the proto-

**Table V.**  
**Elastic properties for CBO mullite.**

Temperature		Young's modulus, E		Shear mod, G		Poisson's ratio,
°C	°F	GPa	(lb/in. <sup>2</sup> ) x 10 <sup>6</sup>	GPa	(lb/in.) x 10 <sup>6</sup>	$\nu$
Room temp	Room temp	104.9	15.21	35.9	5.21	0.46
93	200	104.5	15.15	35.7	5.18	0.46
204	400	102.8	14.91	35.3	5.12	0.46
316	600	101.8	14.77	35.0	5.07	0.46
427	800	100.9	14.63	34.5	5.01	0.46
538	1000	99.8	14.48	34.1	4.95	0.46
649	1200	98.9	14.35	33.8	4.90	0.46
760	1400	98.0	14.21	33.4	4.84	0.46
871	1600	95.2	13.81	32.7	4.74	0.46
982	1800	91.7	13.30	31.2	4.53	0.46

**Table VI.**  
**Thermal diffusivity for Allison zircon.**

Temperature		Thermal diffusivity	
°C	°F	mm <sup>2</sup> /s	(ft <sup>2</sup> /hr) x 10 <sup>2</sup>
24	75	3.61	13.99
54	129	3.27	12.67
93	199	2.94	11.39
160	320	2.54	9.84
235	455	2.14	8.29
274	525	1.99	7.71
382	720	1.70	6.59
480	896	1.55	6.01
613	1135	1.36	5.27
723	1333	1.26	4.88
886	1627	1.13	4.38
1096	2005	1.02	3.95

type rotor to the new engine configuration rotor (ECR). Characterization of the first shipment of CBO-sintered alpha SiC ECRs is in progress, including strength determination and spin testing. Preliminary work on the development of reaction-bonded SiC material for the rotor and other components was conducted. Activities on the gasifier scroll assembly continued, with investigation of a brazing operation to complement the sinter joining process.

### Gasifier Rotor

**Sintered alpha silicon carbide.** Efforts at CBO this reporting period focused on fabrication studies for the ECR. A new injection molding tool was procured by CBO for the ECR and fabrication of 100 rotors initiated. These rotors were produced following a process routing based on that established for the prototype rotors. Forty-seven sintered ECRs were received from this 100-rotor order. Nondestructive inspections of these components revealed linear indications and porosity on the surface of a

majority of the rotors, as shown in Figure 34. CBO has identified flow lines generated during the injection molding process as a probable cause of the surface indications. These flow lines are indicative of incomplete consolidation of the injection molding strand. Experience has demonstrated that subsequent processing does not eliminate these green state flaws. CBO is planning to address this problem by the following approaches: a matrix study of injection molding parameters, tool modifications, and transfer molding trials.

The overall disposition of the 47 ECRs is summarized as follows:

Display	1
Machining trials	2
Strength samples	3
Scrap	1
Sectioned	13
Spin tested	3
Spin pending	14
Awaiting evaluation	10
Total	47

Additional characterization of the engine configuration rotors was performed by cutting standard-size four-point MOR test bars from various locations in the rotors. Preliminary strength measurements were obtained on material from both the rotor backface region (radial direction) and from the interior near the exducer (axial direction), as shown in Figure 35. Five rotors were evaluated at CBO, with one rotor sectioned at Allison. The results of these evaluations are summarized in Table IX. Test material from the backface region (radial) registered an average MOR of 383.44 MPa (55.61 ksi). An average strength of 356.40 MPa (51.67 ksi) was observed for bars cut in the axial direction near the exducer. This represents a significant increase in strength over the 203.86 MPa (29.57 ksi) previously observed for the same region in the prototype rotors.

Three sintered alpha SiC rotors were subjected to an

**Table VII.**  
**Bend strength for Allison zircon.**

Tensile surface condition and temperature	Date tested	Average MOR		Standard dev		Number of bars tested
		MPa	ksi	MPa	ksi	
As-fired, room temp	May 1982	167.48	24.29	30.41	4.41	11
Machined, room temp	Dec 1982	177.06	25.68	16.34	2.37	5
Machined, 1000°C (1832°F)	Dec 1982	164.79	23.90	14.82	2.15	3

**Table VIII.**  
**Young's modulus and Poisson's ratio for Allison zircon.**

Temperature		Young's modulus		Poisson's ratio
°C	°F	GPa	(lb/in. <sup>2</sup> ) x 10 <sup>6</sup>	
Room temp	Room temp	195.1	28.29	0.47
93	200	195.1	28.29	0.47
204	400	195.1	28.29	0.47
316	600	193.9	28.13	0.47
427	800	193.9	28.13	0.47
538	1000	192.8	27.97	0.47
649	1200	192.5	27.92	0.49
760	1400	190.4	27.61	0.49
871	1600	187.9	27.25	0.48
982	1800	186.8	27.10	0.49

overspeed-to-failure spin test to substantiate the flawed nature of this group of rotors. A summary of the results of the spin testing is listed in Table X, along with general NDE observations. The low failure speed exhibited by the ECRs was consistent with the overall NDE inspection results.

Forthcoming sintered SiC rotor development activities include a green body defect study and a preliminary process matrix definition study for the engine configuration rotor. In addition, further spin test characterization activities are planned.

**Reaction-bonded silicon carbide.** The development of a reaction-bonded SiC material for use in injection-molded gasifier rotors is currently being addressed at CBO. These activities have focused on surface preparation techniques designed to remove the excess free silicon on the surface while maintaining strength characteristics and dimensional stability.

Reaction-bonded SiC test bars were injection-molded for strength evaluation. The MOR was determined at room temperature and 1200°C (2192°F) for bars with both as-fired and machined surface conditions, using the standard grit blasting operation to remove the excess free silicon. A technique to minimize surface clean-up was also investigated. This involved coating the bars prior to siliconization with a slurry to inhibit wetting by the molten silicon. A summary of the strength results from this study is listed in Table XI.

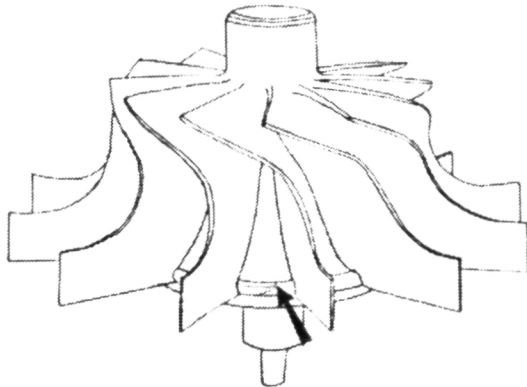
The use of the slurry coating did not appear to significantly affect strength and will not be investigated further. In previous work with reaction-bonded SiC material, the standard surface clean-up operation (grit blasting) was observed to greatly reduce the strength of the as-fired surface. In this study, however, the strength level was retained to a greater degree. These data indicate that surface removal procedures and processing for injection-molded reaction-bonded SiC material, which yield strengths suitable for the gasifier rotor application, have been identified. Further development activities are planned for thick cross-sectional parts to demonstrate the applicability of this material to components such as the gasifier rotor and possibly to the scroll assembly.

### **Gasifier Scroll Assembly**

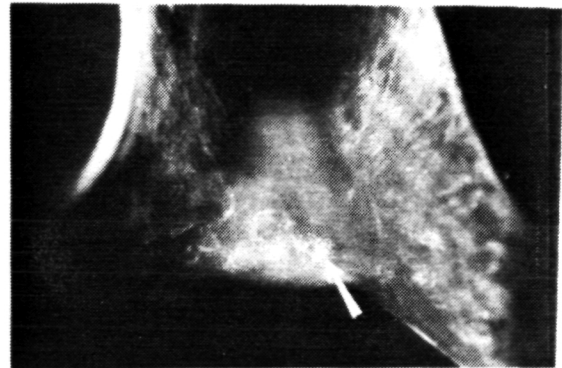
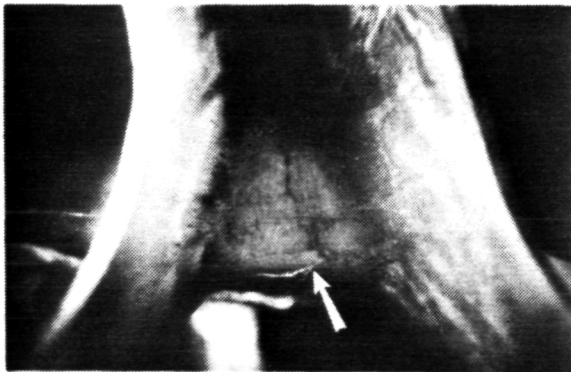
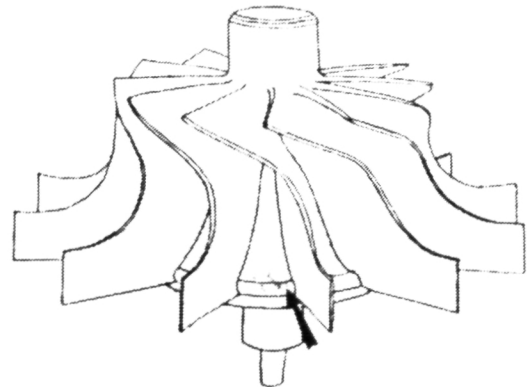
The gasifier scroll assembly, shown in Figure 36, consists of five ceramic components, all produced by CBO from sintered alpha silicon carbide. The connecting duct and scroll are both fabricated by slip casting. The close tolerance shroud and adapter sleeves are made from isopressed silicon carbide and subsequently green-machined to final dimensions. The vane pockets in the shroud are ultrasonically machined after sintering.

The final scroll assembly is produced by sinter-bonding these individual components in sequential fashion. First, the slip cast connecting duct is sintered to full density using appropriate fixturing. Next, the green

## Linear Indications



## Porosity



379783

TE83-1994

**Figure 34. Surface flaws (linear indications and porosity) observed in CBO sintered alpha SiC engine configuration rotors.**

adapter flange is sinter-bonded to this duct. Then the green close tolerance shroud is bonded to the connecting duct in yet another firing operation. Next, this assembly is joined to a green slip cast scroll during a final firing to produce a complete functional scroll assembly. Last, the second adapter sleeve is affixed to the scroll inlet. A total of five sintering operations is required.

Distortion is frequently observed during sintering of large components due to drag between the shrinking part and the stationary setter. This problem has been circumvented by firing the scrolls on a green slip cast plate to minimize the shrinkage differential.

A sintered scroll assembly was supplied to Allison

this reporting period. As a result of handling, the shroud-scroll interface became loose. This assembly was shipped back to CBO for brazing experiments. Subsequent joining was performed with a silicon-based braze, and the braze joint appeared to be sound on visual and X-ray examination. Further development of brazing operations is proceeding.

Scroll assemblies fabricated from siliconized reaction-bonded SiC are also being investigated. Problems with distortion are inherently less with this material due to the minimal shrinkage characteristics of RBSiC (approximately 1%). Component fabrication trials with this material are currently underway.

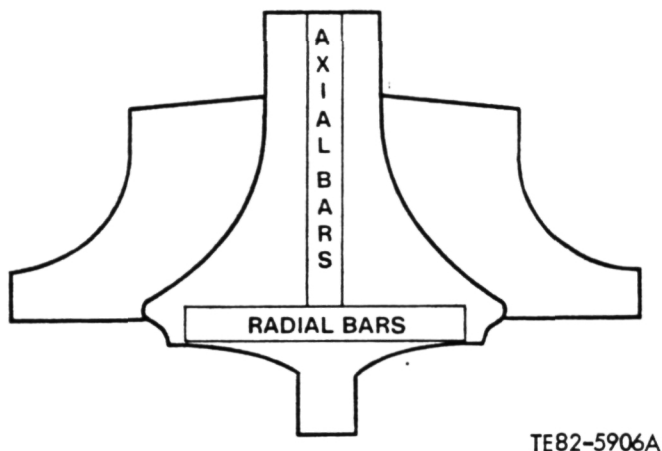


Figure 35. Location of test bars cut from CBO sintered alpha SiC ECRs.

### 9.3 SILICON NITRIDE COMPONENT DEVELOPMENT

#### Gasifier Rotor

Efforts at GTE Laboratories during this reporting period have continued to focus on the development of the injection molding technology required to fabricate AGT gasifier rotors of good quality. More specifically, it has concentrated on the reduction and/or elimination of process-related flaws, primarily internal and external cracking.

The fabrication of silicon nitride components by injection molding involves five basic steps. In the first step, the ceramic powders are blended to a uniform composition, then processed to render them highly reactive for sintering to a high density. In the next step (compounding), the ceramic is mixed with an organic thermoplastic binder or series of binders. The injection molding step involves heating the mix above its flow point and injecting it into a

Table IX.  
Strength characteristics of CBO sintered alpha SiC gasifier rotors (ECRs).

Evaluated at	Rotor No.	Location	Strength		Standard deviation		Density- g/cm <sup>3</sup>
			MPa	ksi	MPa	ksi	
CBO	36	Radial	317.24	46.01	19.93	2.89	3.12
	48	Radial	395.64	57.38	84.60	12.27	3.13
	57	Radial	331.37	48.06	36.41	5.28	3.06
	82	Radial	465.55	67.52	45.51	6.60	3.10
	91	Radial	407.08	59.04	32.75	4.75	3.10
	Average:		383.84	55.67	43.85	6.36	3.10
CBO	36	Axial	523.26	75.89	51.09	7.41	3.06
	48	Axial	287.87	41.75	59.50	8.63	3.07
	57	Axial	295.73	42.89	79.09	11.47	3.07
	82	Axial	360.19	52.24	12.32	16.29	3.06
	91	Axial	317.38	46.03	32.20	4.67	3.04
	Average:		356.89	51.76	67.09	9.73	3.06
Allison	13	Radial	381.43	55.32	58.56	8.49	3.10
	13	Axial	353.92	51.33	57.85	8.39	3.07

Table X.  
Spin test summary

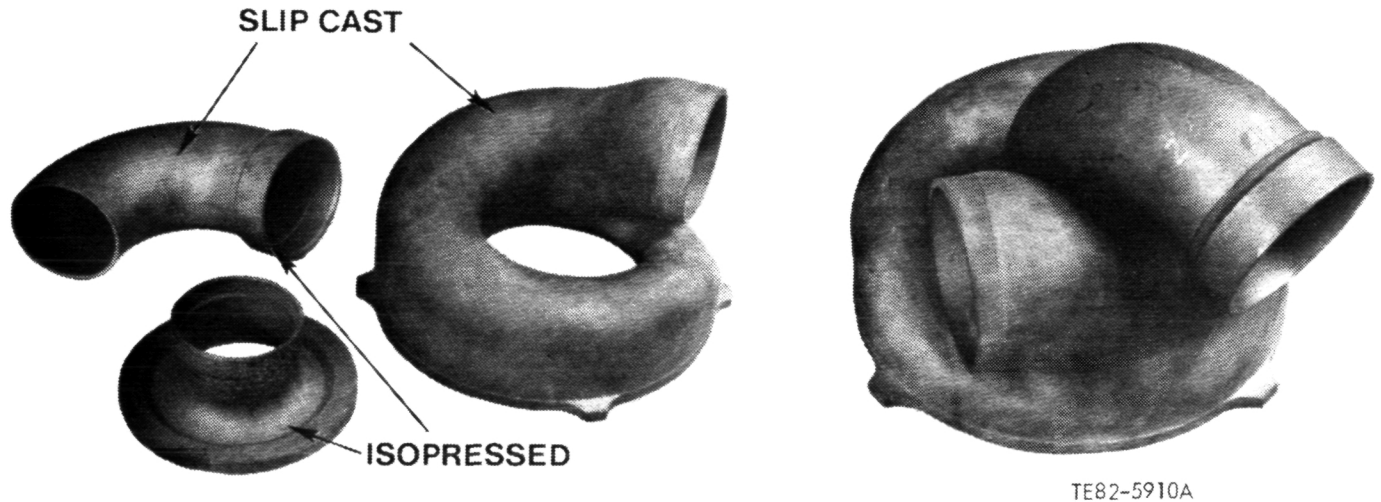
Test date	Rotor No.	Burst Speed-rpm	NDE
22 October 1982	FX 30549	75,000	Mold lines
22 October 1982	FX 31572	48,500	Porosity and cracks
24 November 1982	FX 31566	33,500*	Linear discontinuities

\*Spun with zircon insulator and shaft simulator; stub shaft fracture; not a valid burst test

**Table XI.**  
**Strength characteristics of CBO injection-molded reaction-bonded SiC.**

<u>Temperature</u>	<u>Tensile surface*</u>	<u>Coated or uncoated</u>	<u>Four-pt MOR</u>		<u>Standard deviation</u>		<u>Sample size</u>
			<u>MPa</u>	<u>ksi</u>	<u>MPa</u>	<u>ksi</u>	
Room temperature	As-fired	Uncoated	514.71	74.65	66.19	9.60	16
	Machined	Uncoated	506.78	73.50	94.88	13.76	12
	Machined (not annealed)	Uncoated	484.17	70.22	111.70	16.20	8
1200°C (2192°F)	As-fired	Coated	447.07	64.84	87.84	12.74	8
	Machined	Coated	484.86	70.32	73.71	10.69	7
	As-fired	Uncoated	481.62	69.85	66.12	9.59	9
	Machined	Uncoated	600.62	87.11	107.77	15.63	9
	Polished	Uncoated	510.09	73.98	41.30	5.99	2

\*All specimens annealed unless otherwise specified.



**Figure 36. CBO sintered alpha SiC gasifier scroll assembly.**

relatively cold metal die where the mix solidifies. The fourth process step involves thermal removal of the binders, leaving behind a nondisrupted ceramic structure. The final step is consolidation by sintering. The total process flow chart (designated AYG-100), along with NDE inspection points, is shown in Figure 37.

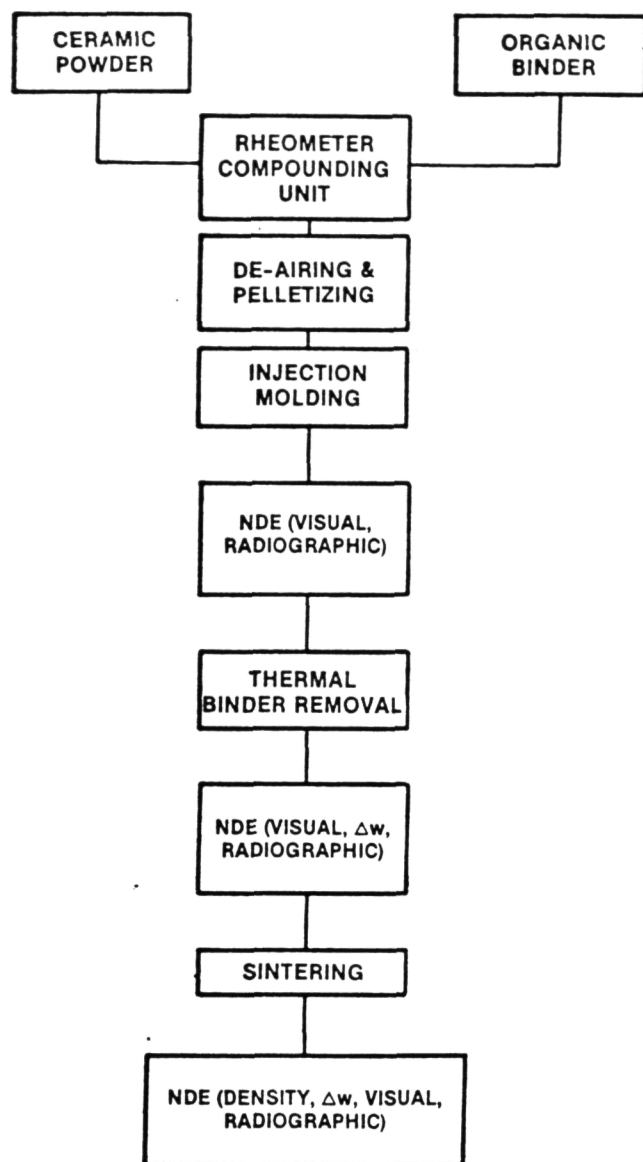
Prior injection molding studies, which were conducted with IR&D funding, have resulted in the establishment of a powder/binder system with an associated process routing, which yielded visually and radiographically flaw-free green rotors. However, subsequent inspection after sintering revealed the presence of two types of flaws: surface cracking at the blade/hub intersection and internal laminations, shown in Figure 38.

Recent studies have identified a number of process-

ing modifications that have demonstrated considerable promise for the reduction and/or elimination of the previously observed difficulties with external and internal cracking. These investigations included modifications in the injection molding tool, binder development, powder/binder system alterations, and improvements in both the binder removal and sintering processes.

**Molding.** Increasing the gate diameter of the injection molding tool has resulted in an improved fill pattern with considerably less air entrapment within the part. It has also eliminated the need for a heated sprue configuration to achieve good quality, as-molded rotors of uniform green density throughout the entire cross section.

**Binder development.** Evidence has been gathered that the surfactant utilized in the binder formulation can



TE83-1995

Figure 37. Process routing (AYG-100) established for GTE injection-molded sintered  $\text{Si}_3\text{N}_4$  rotors.

play a role in reducing the tendency to form internal cracking. Although this concept requires further study prior to recommending a change in the binder formulation, a new surfactant appears to have some advantages over surfactants previously used.

**Powder/binder system.** A reduction in the volume loading of powder with concurrent optimization of the molding pressure (to prevent incomplete filling or overpressure in the die) virtually eliminated internal cracking. It appears that these conditions generated a more uniform stress situation in the mold and helped eliminate the laminations or pressure cracks.

The addition of 10% unprocessed powder to the

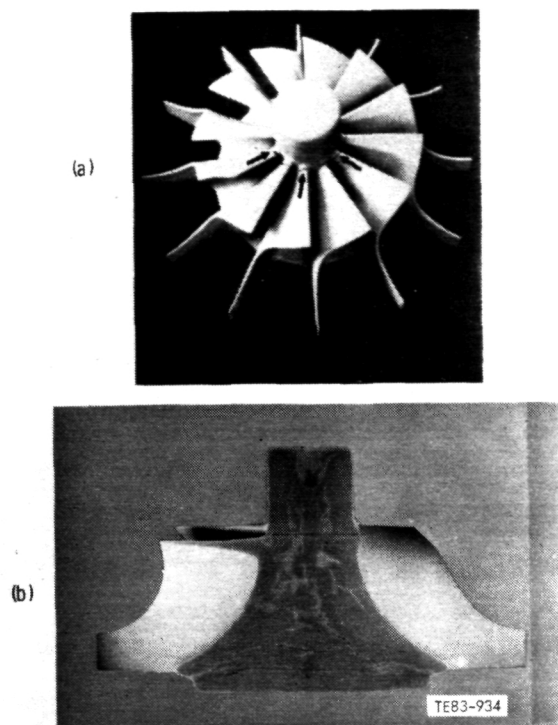


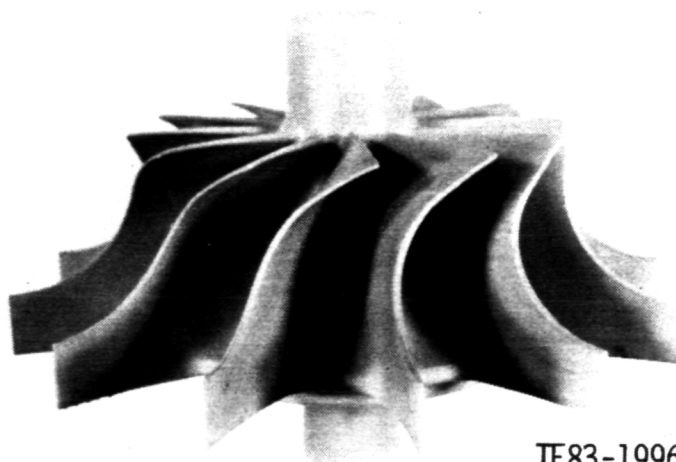
Figure 38. Typical flaws observed in sintered  $\text{Si}_3\text{N}_4$  rotors: (a) surface cracking and (b) internal laminations.

milled powder also greatly reduced the internal cracking. This was attributed to the needle-shaped unprocessed powder minimizing particle rearrangement, thereby reducing differential shrinkage inside the part.

**Binder removal.** The systematic pattern of cracks at the tops of the blades adjacent to the exducer has been controlled by minimizing the tendency of the support setter material used in binder removal to "wick" (remove binder as a liquid) and by positioning the rotor exducer down during binder removal. The use of a low wicking setter material, such as calcined  $\text{Si}_3\text{N}_4$  powder, also reduces other forms of surface-connected cracks generated during binder removal. This has eliminated any advantage or need to coat rotors prior to binder removal.

**Sintering.** A modified sintering technique developed by GTE laboratories has significantly reduced cracking in sintered AGT gasifier rotors. This has raised the density of sintered crack-free rotors, theoretically, to as high as 97%.

Inspections of sintered GTE  $\text{Si}_3\text{N}_4$  rotors received this reporting period, which incorporated these processing modifications, revealed a greatly reduced incidence of the external and internal cracking. One of the most recent sintered rotors is shown in Figure 39. Future development activities will focus on additional optimization of the processing sequence. Concurrently, spin test characterization of rotors will be conducted.



TE83-1996

Figure 39. GTE injection-molded sintered  $\text{Si}_3\text{N}_4$  gasifier turbine rotor.

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## X. CONTROLS DEVELOPMENT

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The controls effort during this period has been to integrate and evaluate the control system with the AGT 100 engine. The flexibility of a digital electronic control has become evident while supporting the initial engine testing.

On the original attempts at running the engine, certain control hardware modifications became necessary or desirable for improved control performance. However, these modifications were easily made, and quick engine test confirmation was possible.

A low voltage shutdown circuit was added to the electronic control unit (ECU) to minimize control malfunction due to power line spikes and electromagnetic interference. Software changes were also made to decrease the vulnerability of the control to electromagnetic interference (EMI). These changes were verified by employing a "chattering relay" to introduce EMI into the unit.

A new method of handling the thermocouple signal conditioning was incorporated into the control. This new method, which has been effectively utilized on another program, improves the resolution of the temperature channels by a factor of three. This will allow better accuracy of fuel scheduling and temperature limiting in the control.

The fuel flow control range was increased by expanding the drive current capability to the throttle valve from 250 mA to 300 mA. The upper limit on the fuel was increased by 0.9 kg/s (2 lb/hr).

As would be expected for a new engine, the control software experienced the most change during the initial running. This demonstrates the need for a flexible digital control. Manipulation of fuel schedules, timers, or other

constants can be made quickly while maintaining all of the safety features built into the control. Safety shutdowns were experienced during initial operation, possibly preventing serious damage.

Speed governing was achieved while running stabilized at idle. The control scheme used in governing will apparently handle the task quite effectively, and no major changes in the control logic are foreseen.

Successful operation was demonstrated on the pilot and start nozzles in the engine. Main nozzle flow was demonstrated in bench tests with the nozzle removed from the engine.

Control of the burner variable geometry (BVG) and the inlet guide vanes (IGV) was successfully demonstrated on the engine.

The control console has been the operator's interface with the engine throughout the engine testing. The console allows manual open loop control of gasifier speed, BVG, IGV, and power transfer clutch. It also permits a bias adjustment to the turbine outlet temperature (TOT) limit of  $-315.5^{\circ}\text{C}$  to  $37.8^{\circ}\text{C}$  ( $-600^{\circ}\text{F}$  to  $+100^{\circ}\text{F}$ ). Manual selection of fuel flow from the start to the main nozzle and a manual cranking operation are two more features of the operator's console.

A test simulator, which has the capability of synthesizing all of the control's inputs and outputs, was built. The test set is used to validate the control software after a change is made to ensure correct operation. A special cable was constructed, which allows a checkout of the fuel system and safety shutdowns while the engine is on the test stand.

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## **XII. SUPPORTIVE MANUFACTURING, COST, AND MARKETABILITY**

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### **12.1 MANUFACTURING FEASIBILITY—PONTIAC MOTOR DIVISION**

Manufacturing feasibility studies at Pontiac are concentrated in two areas: (1) the Engine Component Machining and Assembly Manufacturing Engineering Department and (2) the Pressed Metal Manufacturing Engineering Department. As reported in the previous semiannual report (Ref 1), the manufacturing feasibility analysis based on detail drawings was concluded on a majority of the engine components. These studies were based on normal high-volume production processing and cost estimating procedures. The manufacturing analysis effort has continued during this reporting period as follows.

#### **Engine Manufacturing**

Manufacturing feasibility analysis efforts have focused on refinements to the manufacturing process routings of engine components that could benefit from improved machining procedures. The adaptation of current high-technology, low-volume machining techniques to high-volume component production is also being examined for the AGT 100. This effort has concentrated primarily on the utilization of laser drilling of holes and on consultation with machine vendors concerning the requirements for friction welding of low-carbon steel hubs onto gear forging blanks. There has also been effort devoted to the adaptation of automation to the assembly of the engine components on a high-volume basis. These machining and assembly techniques will be incorporated in the manufacturing processing for the reference power-

train design (RPD) engine component revisions that evolve from the dynamometer engine test program.

#### **Pressed Metal Manufacturing**

Manufacturing feasibility analysis efforts continued in this department on the major sheet metal components of the engine assembly. An experimental die tryout program is being formulated for use in determining the draw and forming characteristics and limitations of the SAE 4130 steel specified for the major sheet metal components. The experience gained during this experimental program will lead to further refinements and suggestions to simplify and reduce the cost of the major sheet metal components in the RPD engine.

### **12.2 COST ANALYSIS—PONTIAC MOTOR DIVISION**

The Industrial Engineering Department at Pontiac has continued to develop and refine a cost analysis of the engine assembly based on the manufacturing analysis inputs received from Manufacturing and Pressed Metal Engineering and from cost quotes received to date from GM-Allied and outside suppliers. There has also been a continuing effort to identify outside suppliers that are willing to formulate cost quotes on the purchased engine components. Pontiac has found that certain cost quotes requested from outside suppliers have not been returned, as the suppliers apparently are unwilling to devote manpower to answer inquiries on a project without near-term production potential.

## APPENDIX A. TERMS AND DEFINITIONS

AGT	advanced gas turbine	lb	pound
AGT 100	the AGT model being developed by Allison	lbf	pound force
AS	aluminum silicate	lbm	pound mass
BU	build number	m	meter
BVG	burner variable geometry	mA	milliampere
°C	degrees Celsius	mm	millimeter
CBO	Carborundum Company	Mod I	the first design of AGT 100 using some ceramic hot section components
CGW	Corning Glass Works	Mod II	the second AGT 100 design with ceramic hot section
cm	centimeter	MOR	modulus of rupture
DDA	Detroit Diesel Allison (now Allison Gas Turbine Operations)	MPa	megapascal
DOE	U.S. Department of Energy	N	force (Newton) or speed of rotation (rpm)
E	Young's modulus	N1	gasifier speed of rotation
ECR	engine configuration rotor	N2	power turbine speed of rotation
ECU	electronic control unit	NASA	National Aeronautics and Space Administration
EDR	Engineering Development Report (of Allison)	NDE	nondestructive evaluation
EMI	electromagnetic inspection	O/B	outboard
EMTL	Energy Materials Testing Laboratory	PMD	Pontiac Motor Division of General Motors
°F	degrees Fahrenheit	psig	pounds per square inch gage
ft	foot	RBSiC	reaction-bonded silicon carbide
G	Shear mod	Ref	reference
GM	General Motors Corporation	RPD	reference power-train design
GPa	gigapascal	RTV	room temperature vulcanizing
GTE	General Telephone and Electronics Corp	s or sec	second
green machining	machining a ceramic before it is fired	SAE 4130	moly steel containing 39% C and 51% Mg, along with P, S, Si, Cr, and Mo
h or hr	hour	S/N	serial number
I/B	inboard	TIT	turbine inlet temperature
IGV	inlet guide vane	TOT	turbine outlet temperature
in.	inch	$\bar{\alpha}$	average coefficient of thermal expansion
kg	kilogram	$\Delta$	difference between two measurements, e.g., $\Delta T$
kPa	kilopascal	$\eta$	efficiency
ksi	thousand pounds per square inch	$\nu$	Poisson's Ratio, $E/2G - 1$
L	liter		
LAS	lithium aluminum silicate		

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## REFERENCES

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1. H. E. Helms, R. A. Johnson, R. K. Gibson, L. B. Smith, "Advanced Gas Turbine (AGT) Power-Train System Fifth Semiannual," DOE/NASA/0168-5, NASA CR-168056, DDA EDR 11185, August 1982.

1. Report No. NASA CR-168235		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle  ADVANCED GAS TURBINE (AGT) TECHNOLOGY DEVELOPMENT				5. Report Date April 1983	
				6. Performing Organization Code	
7. Author(s) Engineering Department, Allison Gas Turbines				8. Performing Organization Report No. EDR 11443	
9. Performing Organization Name and Address Allison Gas Turbine Operations General Motors Corporation P.O. Box 420 Indianapolis, IN 46206-0420				10. Work Unit No.	
				11. Contract or Grant No. DEN 3-168	
				13. Type of Report and Period Covered Contractor Report	
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Vehicle and Engine Research Development Washington, D.C. 20545				14. Sponsoring Agency Code DOE/NASA 0168-6	
15. Supplementary Notes Semiannual report, prepared under Interagency Agreement DE-AI01-77CS51040. Project Manager P. T. Kerwin, Transportation Propulsion Division, NASA Lewis Research Center, Cleveland, Ohio 44135					
16. Abstract Technical work on the design and effort leading to the testing of a 74.5 kW (100 hp) automotive gas turbine is described for the period July through December 1982. This is the sixth semiannual report. The first build of the AGT 100 was completed 9 July 1982, and by the end of the calendar year, five builds had been evaluated. The engine structure, bearings, oil system, and electronic control have been successfully demonstrated, with no shaft dynamics or other vibration problems encountered. Areas identified during the five tests, which require modification, are the scroll retention features, and transient thermal deflection of turbine backplates. Modifications have been analyzed and designed and are in the fabrication process; testing with these new turbine components will begin early in calendar year 1983. Scroll retention is being addressed by modifying the seal arrangement in front of the gasifier turbine assembly, which will increase the pressure load on the scroll in the forward direction and thereby increase the retention forces. The backplate thermal deflection is being addressed by geometric changes and thermal insulation to reduce heat input. Combustor rig proof testing of two ceramic combustor assemblies has been completed. Except for the combustor domes, two sets of ceramic components (combustor body, pilot tube, and dilution bands) have been qualified for engine testing. The combustor dome design has been modified to incorporate slots and reduce sharp edges, which should reduce thermal stresses. Additional ceramic combustor rig testing will be conducted as more ceramic parts become available. The evaluation of regenerator system flow distribution revealed significant potential losses in regenerator effectiveness due to maldistribution of flow. Design modifications have regained almost all of the lost effectiveness with only a small increase in pressure drop, making the regenerator drive system ready for incorporation into the engine. The initial electronic control system hardware has been bench tested, has interfaced successfully with test stand systems, and has been very instrumental in successfully controlling and protecting the engine during the engine testing to date. Rotor attachment/thermal barrier work has progressed at Carborundum Company (CBO) using mullite and at Allison using zircon. The development work has focused on techniques to sinter these barrier materials onto the ceramic rotors with successes for both material systems. Silicon carbide structural parts, including engine configuration gasifier rotors (ECRs), preliminary gasifier scroll parts, and gasifier and power turbine vanes have been fabricated and tested.					
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